ASTRONOMICAL PHYSICS

BY

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D S O , M A , F R A S , F INST P

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WITH THIRTY TWO PLATES

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PREFACE

THIS book was projected in days of comparative freedom for astronomical work before the break caused by the European War It became subsequently the spare time occupation of a busy teacher It contains doubtless sins of commission, but the writer is more conscious of the sins of omission caused by trying to compress a large and growing subject within a given space His aim has been to provide a useful book on the subject for the student, and one which every astrophysicist and not a few spectroscopists would want constantly within reach This he has attempted by giving full references, especially to modern investigations, and more particularly by including in the appendices a number of tables which at present have to be hunted up each in one of a dozen scattered volumes Should a fresh edition of the book be required—and the rate at which new knowledge on its subject matter is pouring in justifies a hope of a later and revised edition—the writer would gladly add other tables which may be suggested by the experience and needs of other workers in the field

It only remains for the writer to express his indebtedness to many colleagues and friends for kindly assistance To Professor Newall, who has helped more often and more widely than he knew, the writer owes a

deep personal debt   In suggestion and friendly discussion his wide knowledge of the subject matter of the book has been freely accessible, he has further supplied several plates and offered facilities for preparing other plates, which have been of great help   Mr Baxandall has helped greatly with the chapter on "Stellar Classification," and has prepared Appendix VIII   Mr Butler has prepared several plates and figures, and has been particularly helpful with the chapter on "The Sun" To the Council of the Royal Society, the Munich Academy of Science, the Editors of the *Astrophysical Journal*, the Astronomer Royal, the Directors of the Cambridge, Edinburgh, Lick, Lowell, Meudon, Norman Lockyer, Mount Wilson, Victoria and Yerkes Observatories, hearty thanks are due for kindly allowing the publication of many of the plates in the book, while members of their staffs have been exceedingly kind in preparing photographs or plates for publication   In particular the writer would wish to express his thanks to Monsieur Deslandres for his photographs, and to Dr J S Plaskett and Mr H H Plaskett for the care taken in selecting the material for Plates 23 and 24 To Mr W H Manning the writer is especially indebted for the trouble taken in preparing the photographs for the publishers   Lastly, the writer wishes to thank Mr E A Milne and Dr W M Smart for reading the manuscript, for their timely corrections and helpful suggestions

The standard notation adopted at the International Astronomical Union at Rome in 1922 has been used throughout

CAMBRIDGE,
August, 1924

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LIST OF THE PRINCIPAL ABBREVIATIONS
USED IN THE FOOTNOTES

Phil Trans	Philosophical Transactions of the Royal Society of London
Proc R S	Proceedings of the Royal Society of London
M N R A S	Monthly Notices of the Royal Astronomical Society of London
Ap J	Astrophysical Journal
A J	Astronomical Journal
A and Ap	Astronomy and Astrophysics
A N	Astronomische Nachrichten
C R	Comptes Rendus de l'Académie des Sciences, Paris
Potsdam Pub	Publikationen des Astrophysikalischen Observatoriums zu Potsdam
Harvard Annals	Annals of the Harvard College Observatory
H C O Cir or Bull	Circular or Bulletin of the Harvard College Observatory
Pub D A O	Publications of the Dominion Astrophysical Observatory, Victoria, B C
Pub A S P	Publications of the Astronomical Society of the Pacific
Phil Mag	Philosophical Magazine
Proc N A S	Proceedings of the National Academy of Sciences, Washington
Trans I A U	Transactions of the International Astronomical Union
B A N	Bulletin of the Astronomical Society of the Netherlands
Pop Ast	Popular Astronomy
Jour B A A	Journal of the British Astronomical Association

PLATE 1
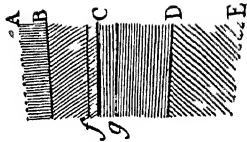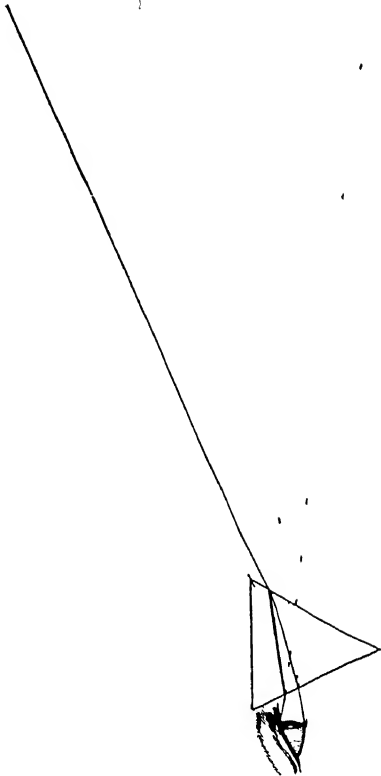
WOLLASTON'S DIAGRAM OF THE DARK LINES OF THE SOLAR SPECTRUM

ASTRONOMICAL PHYSICS

CHAPTER I

MAINLY HISTORICAL

1 Early Observations —In the history of the forward movement of any science there can be traced a series of investigations, which to the later student stand out as guide-posts, leading from areas of entrenched knowledge through what had long been " no man's land " into newly-won territory   It is difficult to say for astrophysics exactly where the series of guide-posts begins, but, if we take time to be an important factor in deciding the starting-point, we can ignore Newton's discovery in 1675 of the composite nature of white light and commence with Wollaston's discovery in 1802 * of the dark lines in the solar spectrum On viewing through a prism of flint glass, a beam of day-light admitted to a darkened room by a crevice one-twentieth of an inch broad, Wollaston noted (Plate 1) that the beam was separated by dark lines into four colours—red, yellowish-green, blue, and violet—and concluded that he had found the elementary colours that make up white light   Wollaston further noticed that if the blue light from the lower part of a candle flame was examined similarly through a narrow slit and a prism a series of bright images were formed, one of which corresponded with the division between blue and violet in the solar spectrum

Phil Trans , xcii 378, 1802

The suggestion underlying this coincidence was not to be developed for many years   Meanwhile a much more accurate and detailed examination of the dark or absorption lines of the solar spectrum was made in 1814 by Fraunhofer * Using a narrower slit, a telescope to view the spectrum and a more elaborate method of plotting the positions of the lines, he increased Wollaston's seven lines in the solar spectrum to 574 , further, he slightly widened the range of spectrum examined, and he mapped out all the lines observed   Some of the stronger lines or groups he identified by letters—A, a, B, C, D, E, b, F, G, H, which have remained in general use to the present day †   (Plate 2)

Among many fresh points brought out by Fraunhofer may be mentioned the following   The focus of the telescope through which the spectrum was observed had to be altered in order that an observer might see clearly the lines in the different parts of the spectrum   Reflected sunlight from Venus showed the strongest lines seen in the solar spectrum [D, E, b, F], while the light of Sirius gave three strong lines not resembling anything found in the solar spectrum   In fact, the stars differed from each other as well as from the sun in the prismatic analysis of their light Light from various terrestrial sources also differed in the character of the bright or emission lines produced   Fraunhofer noted the coincidence of the dark [D] lines of the solar spectrum with a pair of bright lines observed in the light from the flame of a lamp and their resemblance in strength and the equality in separation   Thirty-five years elapsed before this observation was repeated, and then it

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* *Denkschriften der Königlichen Acad d Wiss zu München,* v 202 1814

† The International Astronomical Union, Rome, 1922, adopted a recommendation to enclose these letters in square brackets when used for lines in the spectrum in order to avoid confusion with other notations

PLATE 2

FRAUNHOFER'S MAP OF THE SOLAR SPECTRUM
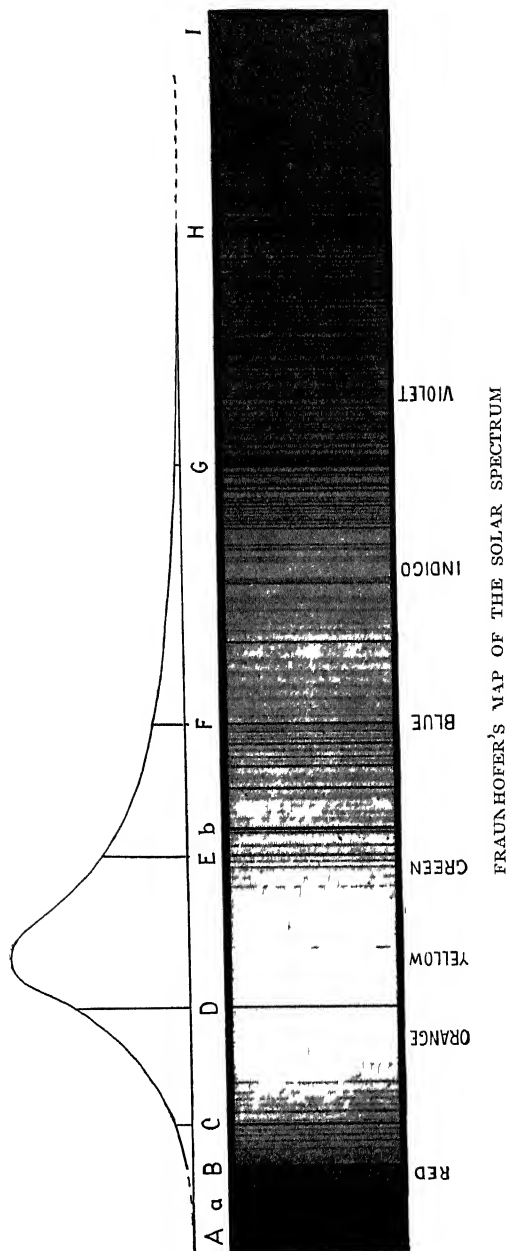
was done in a manner which, for the first time, threw light on the significance of the coincidence

Foucault, speaking at the Societe Philomathique de Paris in 1849,* reported that, having noticed two lines in the spectrum of the carbon arc which resembled the [D] lines in the solar spectrum, he had by means of a convergent lens projected a solar image on to the arc and had observed the two spectra superposed   The bright double line of the arc coincided exactly with the dark double line of the solar spectrum   Further, the arc absorbed the lines [D] of the solar light, which appeared darker than usual when viewed through the arc, and, when a bright point which gave a continuous spectrum was viewed through the arc, the [D] lines appeared dark as in the solar spectrum   Thus, the arc offered us a medium which emitted the [D] lines on its own account and at the same time absorbed them when they came from elsewhere   The [D] lines only appeared weakly when the arc was struck between iron or copper poles, but could at once be enormously strengthened if the poles were touched with potassium or sodium   The source of the [D] lines was not fully determined, but " the pheno- menon seemed to constitute a pressing invitation to study the spectra of the stars, for if this same ray was found there, stellar astronomy would obtain useful results from it "   The invitation was, however, not to be accepted for some years, and it was not until 1859 that the next, and perhaps the most fundamental, step towards the new science was taken by Kirchhoff at Heidelberg

   2   The Origin of Dark Spectral Lines —In the course of an examination of the spectra of coloured flames by Bunsen and Kirchhoff,† the following observations were made   A solar spectrum was formed by projection and the rays,

* *L Institut* xvii 45 1849
   † *Monatsberichte d K Preuss Akad d Wiss zu Berlin* 1859
662

before they fell on the slit, were passed through a powerful salt-flame " If the sunlight were sufficiently reduced, there appeared in the place of the two dark lines D two bright lines , if, on the other hand, its intensity surpassed a certain limit, the two dark lines D showed themselves in much greater distinctness than without the employment of the salt-flame   I conclude," said Kirchhoff, " from these (and other) observations that coloured flames, in the spectra of which bright sharp lines present themselves, so weaken rays of the colour of these lines, when such rays pass through the flames, that in place of the bright lines dark ones appear as soon as there is brought behind the flame a source of light of sufficient intensity   I conclude further that the dark lines of the solar spectrum, which are not evoked by the atmosphere of the earth, exist in consequence of the presence in the incandescent atmosphere of the sun, of those substances which, in the spectrum of a flame, produce bright lines at the same place   We may assume that the bright lines agreeing with D in the spectrum of a flame always arise from sodium contained in it , the dark line D in the solar spectrum allows us, therefore, to conclude that there exists sodium in the sun's atmosphere "

This explanation of the origin of Fraunhofer's lines authorized conclusions respecting the material constitution of the atmosphere of the sun (Plate 3), and suggested to Kirchhoff an application to the brighter fixed stars   Luckily this time, the challenge was not allowed to pass unnoticed It came at a time when a vague longing after newer methods of observation for attacking many of the problems of the heavenly bodies was occupying the mind of a young amateur astronomer, by name William Huggins   The news of Kirchhoff's discovery was to him, he said,* " like the coming upon a spring of water in a dry and thirsty land   A feeling as of inspiration seized me   I felt as if I had it now in my

* *The Nineteenth Century Review*, June, 1897

PLATE 3

SUN

ARC

SR

FE

MN

AL
CA

C
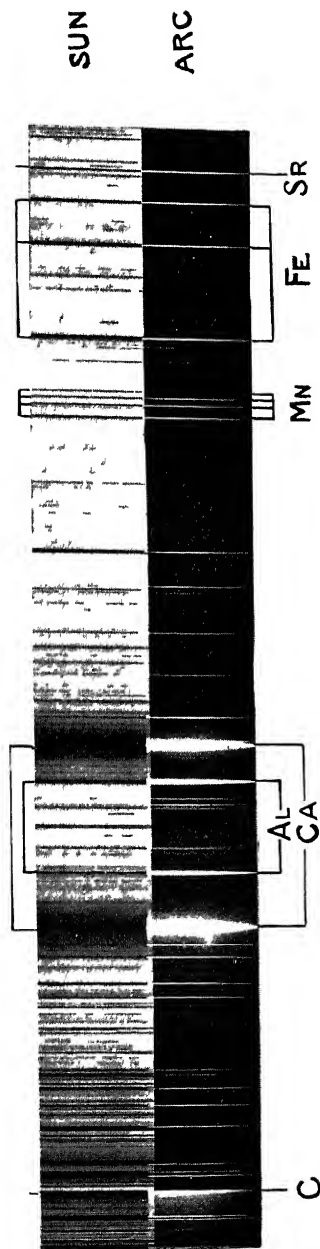
COMPARISON OF SOLAR AND ELECTRIC ARC SPECTRA OF CALCIUM, STRONTIUM, IRON, MANGANESE, ALUMINIUM, CARBON, ETC., SHOWING PRESENCE OF THESE ELEMENTS IN SOLAR ATMOSPHERE

Photographed by C P Butler with 21 ft Rowland Concave Grating at Solar Physics Observatory, London, 1897
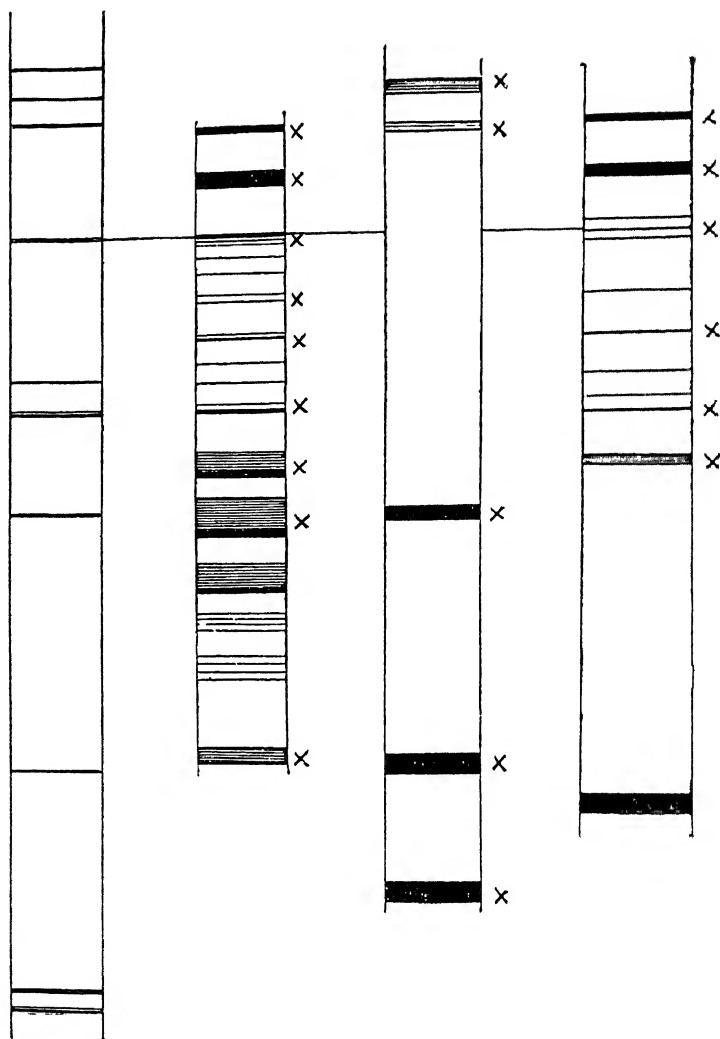
PLATE 4

power to lift a veil which had never before been lifted, as if a key had been put into my hands which would unlock a door which had been regarded as for ever closed to man—the veil and door behind which lay the unknown mystery of the true nature of the heavenly bodies "

3 Early Stellar Researches—Huggins secured the assistance of Professor W A Miller, of King's College, London, in his attack on the very difficult problem of extending Kirchhoff's discovery to the stars With great ingenuity and persistence they overcame the many serious instrumental difficulties Simultaneously with Secchi in Rome, and a month after Rutherfurd in America, Huggins and Miller published, in February, 1863, a preliminary note on stellar spectra * (Plate 4), they were easily first in the field in the careful analysis of stellar spectra which the Royal Society published in the following year † The spectra of the brighter stars were examined simultaneously with the spectra of ten to twenty elements and identifications of lines were made with considerable certainty In part, at least, the riddle of the Universe had been solved The stars, though differing from one another in the kinds of matter of which they consisted, were found to be all constructed on the same plan as the sun and composed of matter identical, at least in part, with the materials of our system A common chemistry was now known to exist throughout the visible universe

A general unity having been established, the next step was to examine the underlying diversity of type and this was first done in detail by Secchi, in 1866 ‡ He observed some 300 stars which he fitted into a framework of four main types The question of stellar classification will be discussed in detail in a later chapter It is mentioned here as it has been a fundamental factor in the development of the science of stellar spectroscopy

* *Proc R S* xii 444 1863　　† *Phil Trans*, cliv 413 1864
‡ *C R* lxiii 621 1866, *A N* lxxiii 129, 1868

4 Introduction of Photography —The extension to spectroscopic work, which was made possible by the introduction of photography, and the enormous increase in accuracy resulting therefrom, entitle it to be included amongst the early sign-posts which pointed out the line of development of the new science of stellar physics   The first photographic spectrum of the sun which was published, was obtained in December, 1872, by Dr Henry Draper *   The earliest recorded attempt at the photography of stellar spectra was made by Huggins and Miller in 1863 , but, owing to instrumental difficulties, the plate secured presented no indication of lines   It was not until 1876 that Huggins secured a photograph of a stellar spectrum showing the stronger lines of the spectrum †   Meanwhile, Dr Henry Draper, in New York, had also obtained, in 1872, photographs of the spectra of several stars ‡   Huggins soon saw the value of replacing the wet plate by the dry plate   Results of importance immediately followed, notably an increase in the accuracy of measurement of stellar lines and the extension of the series of hydrogen lines towards the ultra-violet   In the hands of Balmer and Rydberg this laid the foundation of the study of series in spectra   Many new developments at once became possible, and the science began to branch out along many different lines   Important discoveries and advances were still to be made, but these will be best described in the separate chapters to which they more appropriately belong   Meanwhile, it is necessary to make reference to the instruments used in astrophysical researches and to allied laboratory investigations, so that the account of the later researches may be given without frequent explanatory interruptions

* *American Journal of Science,* vi 401 1873
† *Proc R S* xxv 445 1876
‡ *American Journal of Science* (3) xiii 95 1877 and xviii 419, 1879

INSTRUMENTS

5 The Stellar Spectroscope (*a*) *The Objective Prism and Prismatic Camera* —The first instrument used to examine a star's spectrum consisted of a prism placed in front of the object-glass of a telescope, the prism was large enough for the refracted beam of star light to fill the object-glass of the telescope   A composite beam of parallel rays from the star strikes the outer surface of the prism, corresponding to each element in colour of the incident beam a group of refracted rays emerges from the prism as a parallel beam the direction of the refracted beam depending on the wavelength or colour of the element concerned   This beam gives a point image of the star after passing through the objective of the telescope   Adding the effects of the separate elements we get for the star's image not a point but a narrow line, of width equal to the diameter of the star's image, and ranging in colour from red at one end to violet at the other Corresponding to the absorption lines in the star's spectrum there are gaps in the narrow line-image, but these are very difficult to see, Fraunhofer, who used this instrument, adopted the device of a cylindrical lens to widen the narrow line-image at right angles to its length so as to form a band This cylindrical lens was placed between the prism and the object-glass of the telescope with its axis at right angles to the edge of the prism   The length of the coloured line-image was not changed, but it was widened parallel to itself into a band, and the gaps in the line-image were

changed into dark lines running across the band   In the modern form of the objective prism spectrograph, the prismatic camera, as used at Harvard in the formation of the Draper Catalogue of Stellar Spectra, the eye-piece for observing the spectrum is replaced by a photographic plate, the spectra of a whole field of stars being secured at the same exposure   Instead of using a cylindrical lens to widen the spectra of the stars, the images of the stars are allowed to trail slowly across the plate in a direction parallel to the edge of the prism and to the extent necessary to secure measurable spectra   The prism in front of the object-glass in this instrument is called an objective-prism

(b) *The Direct-Vision Spectroscope* —By the use of five prisms, three of crown glass, and two of flint glass arranged

FIG I
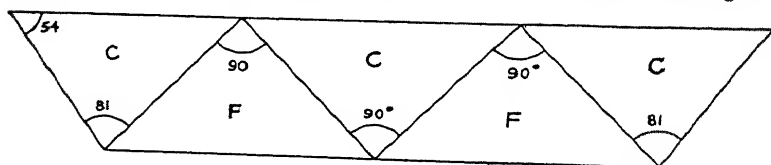
as in the figure, Janssen designed a spectroscope which gave no deviation for a ray of a given wave-length, though rays of shorter or greater wave-length were bent and a spectrum was formed

Thus the tube in which the prisms were mounted could be pointed at a bright line, and if held at the proper angle, the source of light was seen spread out into a coloured band Secchi used this type of instrument for his earlier work It is a handy instrument of use mainly for qualitative examination of stellar or laboratory spectra   It is not an effective type for exact work on stellar spectra, but it can be employed with advantage on very faint spectra when the time involved prohibits the use of photography

(c) *The Prismatic Slit-Spectroscope* —The great draw-

PLATE 5
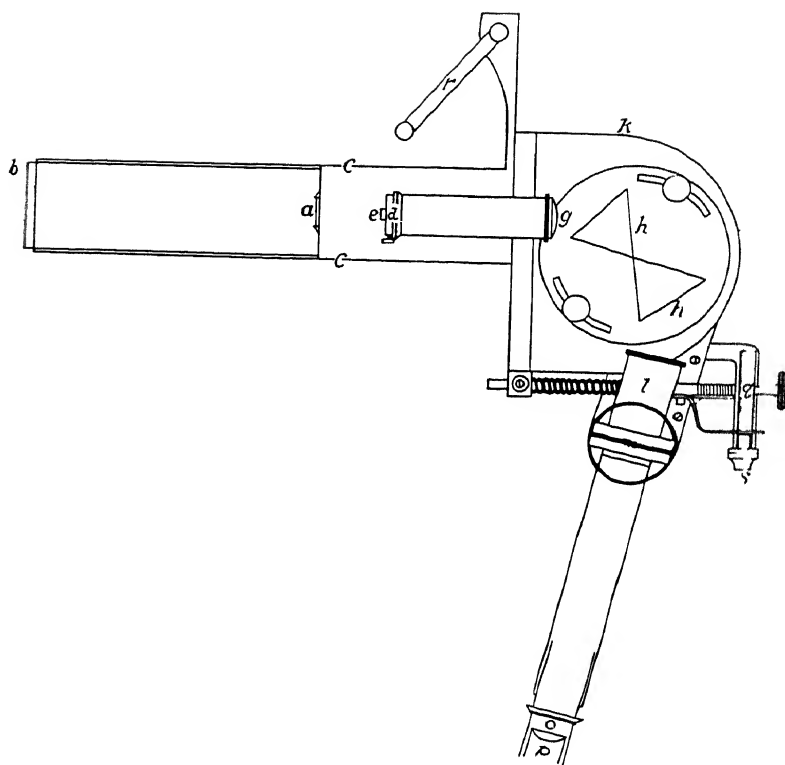
HUGGINS'S FIRST STELLAR SPECTROSCOPE

back of the prismatic camera for stellar work is that it does not admit of any easy and reliable method of comparing the stellar spectrum with that of some known terrestrial source This is important, not merely for identification purposes, but also for all investigations dependent on the exact position in the stellar spectrum (i e the observed wave-length) of lines of known chemical origin Huggins saw from the start the need for the comparison of stellar with terrestrial spectra, and in its essentials the slit-spectrograph of to-day reproduces the features of his first instrument (Plate 5) We will describe this first The image of the star was formed by the object-glass of the telescope and thrown upon a narrow slit The beam of rays converging from the object-glass to the slit was caught by a cylindrical lens placed a little way in front of the slit with its axis at right angles to the slit, so that the point image of the star was broadened slightly along the slit A collimating lens was placed between the slit and the prisms with a principal focus at the slit so that the beam of light from the star image emerged as a bundle of parallel beams on to the prisms Two 60° prisms of flint glass with their edges perpendicular to the refracted beams were used to disperse the beams and the resulting spectrum was viewed through a small achromatic telescope In front of the slit and over half of it was placed a right-angled prism which reflected an image from some terrestrial source of light on to the slit The star's spectrum and the terrestrial spectrum were viewed simultaneously and coincidences of lines in the two spectra could be observed The methods adopted for measuring the positions of lines need not be discussed, as for all exact work photographic plates have replaced the earlier visual observations The development of photographic methods led to several modifications of the apparatus amongst which the following may be mentioned The eye-piece of the spectroscope was replaced by the camera lens and photographic

plate of the spectrograph   The cylindrical lens was abolished, the star being allowed to drift along the slit between two defined marks   This was easily done by setting the slit in the direction of the daily motion, and making the clock run a little slow   By the use of a slow motion control in right ascension the star could be made to trail across the proper portion of the slit as often as necessary   In order to observe the slit and the star's image on it for the purposes of accurate guiding, the jaws of the slit were made of polished speculum metal   The slit was illuminated by a feeble red lamp   The image of the star being wider than the slit, it was possible to view both through an eye-piece and to check the position of the stellar-image on the slit   By slightly tilting the slit-jaws it was possible to arrange that this eye-piece should be outside the beam of rays converging from the object-glass of the telescope to form the image of the star on the slit

The comparison spectrum was generally obtained from an electric arc or spark between metallic electrodes,   an image of the arc or spark was thrown on the slit on each side of the portion of the slit over which the star had trailed —care being taken first to cover by a screen the portion reserved for the star   At first the comparison spectrum was photographed at the beginning and end of the stellar exposure   As a later refinement the comparison spectrum was obtained from a series of short exposures made at regular intervals during a long stellar exposure   The exposure on the star had to be interrupted while the comparison spectrum was being photographed, care being taken that no light from the arc or spark fell on the part of the slit or plate reserved for the star image and spectrum respectively   In the latest designs the comparison spectrum can be added at any time without interfering with the stellar work and without affecting the spectrum of the star

The growing exactitude of photographic work and the

PLATE 6
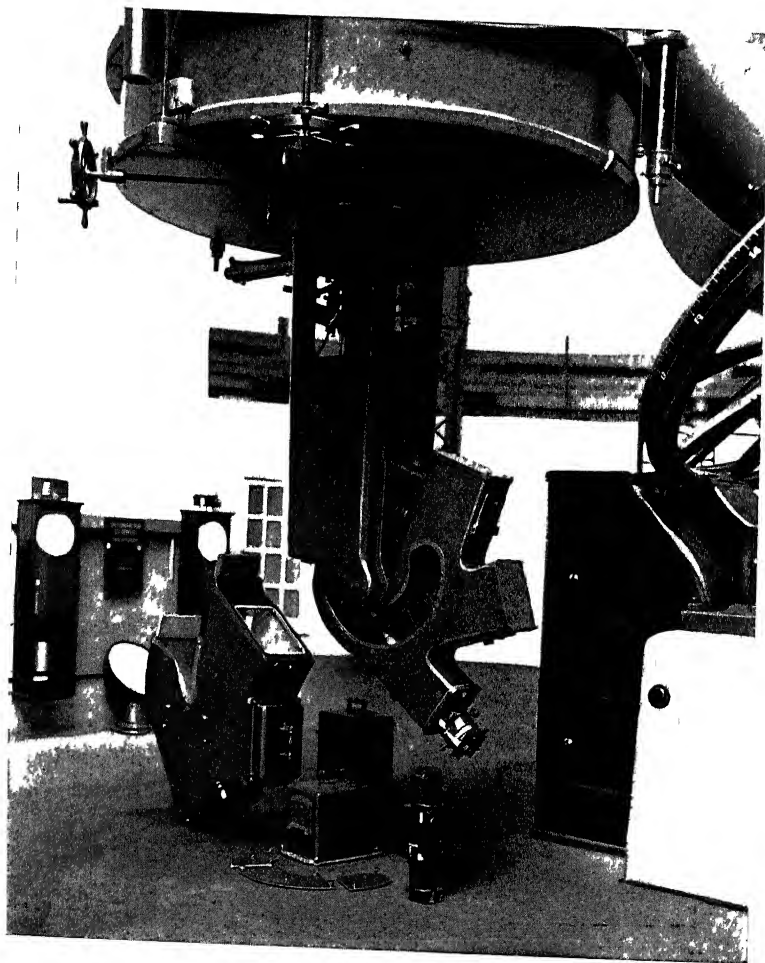
STELLAR SPECTROGRAPH OF THE 72 INCH REFLECTING TELESCOPE AT THE DOMINION ASTROPHYSICAL OBSERVATORY, VICTORIA, B C

increased requirements of the later researches have led to a
further important modification of the simple stellar spectro-
graph designed by Huggins   For all work of high accuracy
the spectrograph has to be kept at as constant a temperature
as possible, and various jackets, warmed by electric currents
have been designed to meet this need   It is not within the
scope of this book to enter in detail into the designs of
spectrographs to meet the requirements of special lines of
work   For each problem there will be one design which
will be the most suitable , the design is, however, severely
conditioned by the amount of light available, and this,
again, depends on the size of the telescope for which the
spectrograph is designed and the faintness of the stars
which it is intended to study   Considerations which have
guided astronomers in the past in the designs of their spec-
trographs have been fully stated elsewhere, and references
are given in a footnote *   (Plate 6)

6 The Grating Spectroscope—So far we have only been
considering spectra formed by the passage of light through
glass prisms   Newton, Wollaston, Fraunhofer all obtained
their results in this way   But in 1821 another method was
devised by the last-named by which the light from an
illuminated slit could be dispersed to form a spectrum or
rather a series of spectra †   When a monochromatic pencil
of rays of light from a slit passes through a collimating lens

* Tulse Hill *A and Ap* xii 117 1893 and *Ap J* i 359, 1895 ,
Lick, *Ap J* , viii 123, 1898 , xi 259 1900 , and xii 274 1900
Yerkes *Ap J* xv 1, 1902   Cambridge *M N R A S* , lxv 608 636
1905   Potsdam *Ap J* , xi 393 1900   Lowell *Ap J* , xx 1, 1904
Mt Wilson *Ap J* xxxv 163 1912   Victoria, *Ap J* xlix 209 1919
Allegheny *Publications of the Allegheny Observatory* Vol II No 1 1912
See also *Ap J* , 1895 for papers by Michelson, Wadsworth and Keeler
For a non-mathematical discussion of the power of a spectroscope,
see " The Spectroscope and its Work, ' by Newall   For a fuller
account of the spectroscope see ' Spectroscopy   by Baly
† *Denkschriften d K Akad d Wiss zu Munchen* viii 1821

so as to give a parallel beam of light, and strikes a grating consisting of a number of evenly-spaced narrow straight and equal apertures parallel to the slit, a bright image of the slit is formed flanked by narrow fainter images symmetrically placed on either side   If the light is composite, as sunlight is, corresponding to each of these images, a spectrum is formed   The observed facts have been explained in terms of the wave-theory of light according to which light is propagated by a series of waves or tremors in the ether   For each element of the spectrum there is a value for the wave-length (i e the interval between the successive crests of the waves) of the corresponding disturbance in the ether   The theory gives a connection between the wave-length of the light, the distance between successive apertures of the grating and the observed angle through which the light giving a particular line of the spectrum is deviated by the grating   Fraunhofer used the method to determine the wave-length of the [D] line for which he first obtained the value 588 8 millionths of a millimetre - correct to I part in 700*   The advantage of the grating over the prism for mapping purposes was obvious   For one thing it gave to each line a corresponding number which had a simple physical meaning independent of the details of the instrument used   Secondly, unlike the prismatic spectrum, the grating spectrum under certain conditions is *normal* or of constant scale per wave-length over a fairly large range, so that once the scale has been accurately determined and a fixed point identified, wave-lengths of lines may be read off at once by comparison with an accurate scale   This does not apply to the original plane grating designed by Fraunhofer, but to the concave grating designed by Rowland in 1882 and mounted and used in the way described below We may note here that Ångström produced in 1868 the

* *Denkschriften d K Akad d Wiss zu Munchen*, viii 1821, pp 28-34   1 millionth of a millimetre = 1 millimicron = 10⁻⁷ cm , and is generally written μμ

fiist normal map of the Fraunhofer lines in the solar spectrum giving the positions of some 1200 lines, of which 800 were identified with lines of common elements, notably iron, titanium, and calcium * The unit he used, a tenth-metre or 10^{-10} metre, is still generally called an Ångstrom Unit, and its use is denoted by placing A after the number expressing the wave-length of a line His map covered the range of wave-lengths from 3933A to 7320A Rowland, who had modified the grating by ruling it on a *spherical mirror,* enlarged Ångström's Tables to about 20,000 lines between wave-lengths 2975A and 7331A and gave his results with much increased accuracy † Rowland's wave-lengths are only now being gradually replaced by the International wave-lengths, of which details will be given later in this chapter Some of the advantages of the grating over the prismatic spectrograph have been indicated The chief disadvantage lies in the faintness of the spectral images formed This has practically limited the grating spectroscope to laboratory and solar work, where it has been used most extensively ‡

The conditions of mounting referred to above which are necessary for securing a normal spectrum are as follows The source of light must lie on the circumference of the circle, tangent to the grating and normal to the lines of the grating at its point of contact, which has as diameter the radius of curvature of the grating The spectra are formed on the circumference of this circle and the *normal* spectrum is the one formed on the diameter of the circle through the point of contact In the mounting adopted by Rowland the grating G and the photographic plate P (bent to the

* " Spectre normal du Soleil ' Upsala, 1868
† ' Preliminary Table of Solar Wave lengths *Ap J* 1 -v See, in particular *ibid* , 1 29 1895
‡ For a description of the 30-foot grating spectrograph used at Mt Wilson Observatory, see *ibid* , xxvii 207, 1908

curve of the circumference of the circle) move on two girders AB, AC, rigidly fastened at right angles to one another , GP is normal to the grating and of fixed length equal to the radius of curvature of the grating, so that P is the centre of curvature of the grating   A source of light at A gives a normal spectrum at P , A, G, P, all lie on the circle on GP as diameter
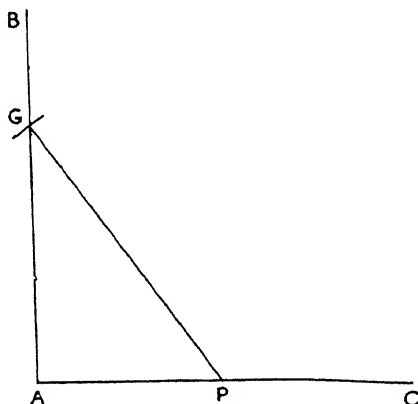
FIG 2

7 The Spectroheliograph —In 1889 G E Hale, afterwards the first director of the Mount Wilson Observatory, designed a modification of the spectrograph which has proved of immense value in advancing the study of the solar atmosphere   The spectroheliograph enables a photograph of the sun's entire disc or of the prominences at its limb to be secured in terms of the light of a given wave-length The principle of the instrument is briefly this   The image of the sun is formed as usual on a screen containing a narrow slit   The light from this slit passes through a train of prisms and mirrors and forms a spectrum in a plane parallel to that in which the solar image lies   A selected line in the spectrum is chosen and made to coincide with a second slit and the

photographic plate is placed close behind the second slit
Then the whole instrument except the photographic plate
is made to move uniformly, at a rate which can be controlled,
parallel to the planes containing the two slits or at right
angles to the beams of light   Thus the first slit passes
across the image of the solar disc and the photograph of
successive elements of the sun's image in light of a given
wave-length is built up on the photographic plate as the
second slit moves across it   There are, as may well be
expected, many niceties of adjustment and design required
for a successful instrument of this nature, but they have
all been most successfully met by its inventor and his
colleagues *

Various modifications of the above design have been
tried by different investigators, the chief points of variation
lying in the shapes of the slits, the movements of different
portions of the apparatus—including the telescope and
mirrors which feed the spectroheliograph—and the details
of the optical train   One point might be briefly mentioned
The image of a long slit through a spectroscope is a curved
line   The use of a straight slit would give a distorted image
of the sun   By curving the first slit so that its image is a
curved slit of identical shape the difficulty of distortion has
been overcome   One closely allied instrument that must
be mentioned is the " *enregistreur des vitesses* " or velocity
recorder of Deslandres   In this case instead of the motion
of solar image and of photographic plate relative to the two
slits being as continuous as possible, it is made up of a
series of small discrete movements †   The photograph is
built up of a series of strips, each of which contains a dark
line   This line is part of an ordinary spectral picture of a

* See for the first account *A and Ap* xii 241 1893, and for a
later design of instrument, *Ap J* , xxiii 54, 1906
† See *Meudon Annales*, iv 19, 1910, and *M N R A S* , lxxiii 327
1913

strip of the sun, the second slit of the instrument being
broad enough to allow the whole width of the line to be seen
and also any distortion of the line due to velocity in the line
of sight of the vapours responsible for the line   (See Plate 13
and Chapter VII below)   The amount of the displacement
from its normal position of the line at any point of the
disc and consequently the motion of the corresponding
gases can be determined by measuring the distance of the
line from an accompanying fiducial line   Thus, the picture
of the sun's disc in the light of a particular wave-length may
be supplemented by a picture showing the behaviour of a
given spectral line at all points of the disc

 8 Measuring Machines and Reductions —When a stellar
or solar spectrum accompanied in general by a known
terrestrial comparison spectrum has been secured by one of
the instruments described above its full value can only be
obtained when it has been measured and the wave-lengths
of the stellar or solar lines have been determined   The
measurements can be made directly, the positions of both
stellar and comparison lines being found on the standard
scale of a comparator or measuring machine   One
systematic error in measurement that has always to be
taken into account is physiological in origin   Lines are
measured too much to the right (or left) by an amount
differing with their breadth and strength   This error is
corrected, at any rate for symmetrical lines, by measuring
the plate in two positions—red end of the spectrum to the
right and then to the left   A residual error may remain
in the measure of close blended or other non-symmetrical
lines   The screw-errors or scale-errors of the measuring
instrument have to be determined with care and the curved
shape of the slit image may have to be taken into account
When the positions of the stellar lines are known relative
to the comparison lines of known wave-length, the calcula-
tion of the wave-lengths of the stellar lines is fairly easy.

If the spectrum is a normal one derived from a grating a simple interpolation gives the correct answer, but if the spectrum is prismatic, the dispersion differs along the spectrum and the reduction becomes slightly more complicated If n is the measured scale value of a given line and λ is its wave-length, then for small ranges of the spectrum the Hartmann-Cornu * formula—

$$\lambda = \lambda_0 + \frac{c}{n - n_0},$$

is sufficiently exact for most purposes The constants λ_0, c, n_0 for any plate may be determined from three lines of the comparison spectrum taken near the extremes and the centre of the range concerned The calculation involved is set out diagrammatically in Appendix II

If a wider range is required, the same formula can be used, but an empirical correction can be added as follows A number of comparison lines, in addition to the three used in determining the constants of the reduction, are measured, and the reduced wave-lengths of these lines are compared with the known values Plotting the residuals against the wave-lengths, we may draw a freehand curve through the points and derive corrections to the reduced wave-lengths for any point in the range Extrapolation outside the extreme standard lines is dangerous, and should be avoided when possible †
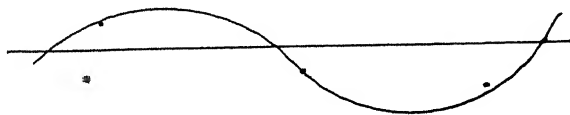
FIG 3

* " Potsdam Pub ," xII , Appendix, p 5 1902
† For a modification of the simple Hartmann-Cornu formula which admits of the use of more than three standard lines see a paper by the author, $M N R A S$, lxxi 663 1911

2

A marked simplification in the calculations required in certain classes of work is obtained by the use of Hartmann's Spectrocomparator * Where the spectrum to be measured is sufficiently like some standard spectrum, e g the solar spectrum, the star spectrum and the standard spectrum are both photographed with the same spectrograph and alongside the same comparison spectrum By an arrangement of reflecting prisms and masks the two spectrograms are brought into the same field of view, alongside each other, care being taken to secure images of the same size Corresponding lines in the standard and stellar spectra are made to coincide in position and then the amount by which one spectrogram has to be displaced to secure coincidence of neighbouring comparison lines is measured From this we can deduce the difference of wave-length between the stellar line and the corresponding line in the standard spectrum

9 Standard Scales of Wave-Lengths —The first table of wave-lengths on a large scale was that of Ångström (referred to in § 6), which appeared in 1868 This was found to be in error owing to a wrong determination of the length of the standard metre at Upsala Thalén corrected the measures and extended the work † Muller and Kempf at Potsdam and Vogel measured over 4000 lines and established the Potsdam system of wave-lengths ‡ Meanwhile Rowland, working with higher dispersion and more powerful apparatus than the Potsdam investigators had been using, was preparing tables of wave-lengths on a much more elaborate scale, and during the years 1895-97 he published his " Preliminary Table of Solar Wave-Lengths " § There are

* *Ap J* xxiv 285, 1906
† *Nova Acta Societatis Upsaliensis* 3rd series, xii 1884
‡ *Potsdam Pub* v 1886
§ *Ap J* , i -v 1895-97 For corrections from Rowland s wavelengths to the International system, see below, Appendix III (*a*)

certain systematic errors in this table due to the use of a
grating and to variations in the physical conditions under
which the spectra were secured, but the table was a splendid
piece of work, and is even now only gradually being re-
placed in astronomical work by later and more accurate
data *

The International Solar Union decided, in 1905, that
a new international standard should be formed   This
was based, not on the [D] line, but on the red line of
cadmium   This line might be said to define the Inter-
national Ångstrom or (I A) unit   In an electric arc of
6 to 10 amperes, under a pressure of 760 mm of mercury
($g = 980\ 67$) in dry air at 15° C , this line has, on the I A
scale, a wave-length of 6438 4696 I A units   This value
was adopted in 1907 by the International Solar Union
(Rowland's Table had been founded on the [D] line of sodium
at 5896 155 $\times$ 10^{-10} m)   By means of intermediate standard
lines in the green Fabry and Buisson, also Pfund and Evers-
heim, subsequently measured 86 iron arc lines by interfero-
meter methods   the means of their three measurements
were adopted by the Solar Union as secondary standards †
A list of these lines is given below in Appendix IV   A list
of tertiary standards measured by several observers working
with concave gratings was given by Kayser at the Inter-
national Solar Union at Bonn in 1913, and is reproduced
below in Appendix V   The International Astronomical
Union meeting at Brussels in 1919 appointed a Committee
to continue the work commenced by the earlier body
The International Solar Union at Bonn had laid down the
conditions of the arc to be used for work on the tertiary

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* For an account of the relations connecting this table to
Rowland's earlier tables and to Prof Kayser's   Normale Aus dem
Bogen-spectrum des Eisens,'' 1900, see Hartmann *Ap J*   xviii
167, 1903
  † *Ibid* , xxxii 215 1909   xxxiii 85 1910   xxxix 94, 1913

standards * Already, however, St John has shown † that the international arc gives lines displaced by the pole effect, i e the wave-lengths are affected by disturbing conditions in the arc that are associated primarily with proximity to the poles of the arc St John suggested as preferable to the arc agreed upon at Bonn, a Pfund arc ‡ 12 mm long, carrying 5 amperes or less, operated between 110 and 250 volts, used over a central zone at right angles to the axis of the arc not more than 1 25 mm in width, and with an iron rod 7 mm in diameter, as the upper electrode He added that the wave-lengths already published are not sufficiently free from pole-effect to comply with the more and more exacting demands that will be made upon such fundamental data

In the report of a committee on wave-lengths of lines to the International Astronomical Union at Rome, 1922, St John gave a further list of secondary and tertiary standard iron lines which had been measured by himself and other workers These fresh lines have been adopted, and have been incorporated below, in Appendices IV and V St John also suggested a number of lines of neon and a number of iron lines outside the range of previous tables as suitable for new standards and indicated which of the old standards ought now to be abandoned

10 (a) Photometers —As one of the important developments of stellar physics is closely identified with stellar magnitudes, a brief description of the more important instruments in use in stellar photometry must be given The wedge photometer was first invented by Pritchard, of Oxford § It consists essentially of a wedge of neutral-tinted glass cemented to a similar wedge of clear glass and made to slide close to the eye-piece of a telescope The scale of the wedge can be determined in the laboratory and

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the relative brightness of stars deduced from the positions on the wedge at which they become invisible   H H Plaskett * has applied the neutral wedge to a photographic study of the distribution of intensity in a star's spectrum , a wedge *uniformly* illuminated along its length by light from a star is placed in front of the slit and the breadth of the resultant spectrum for different wave-lengths provides a measure of the intensity of the corresponding radiation

Difficulty in the application of results found by the wedge photometer arises from the fact that the wedge may show a certain amount of selective absorption   This criti cism does not apply to the Nicol photometer, at any rate in its latest forms   This type was first designed by Pickering, in 1877 † and was used for the Harvard Photometric Observations   The essential point lies in cutting down by an accurately-known amount the light from a standard source so as to make it equal to that of the source under observation , this is done by the use of a double-image prism and a Nicol

During the last three decades photographic photometry has become more and more important   The point of interest lies in the fact that the scale of photographic and photovisual magnitudes is not the same for all stars   This was only to be expected, as the sensitiveness of the eye and of the photographic plate vary in different manner along the spectrum and the maximum spectral intensity of stars also varies from type to type   The magnitudes, m, of stars on the same photographic plate are given in terms of their diameters, d, quite closely by the empirical formula first adopted at the Royal Observatory, Greenwich, ‡

$$m = a - n \sqrt{d}$$

* *Pub D A O* , ii 213, 1923
† See *Harvard Annals* xi 1879 and *Ap J* , ii 89, 1895
‡ *M N R A S* lii 125, 1892

a and *n* are constants depending on the length of exposure and the nature of the plate   A more accurate instrument for determining stellar magnitudes by photographic methods is the objective-grating first used by Prosper Henry * and Wirtz †   It consists of a series of parallel wires or strips of equal width, separated by equal apertures and stretched across the object-glass of a telescope   The normal star-image is accompanied by a series of diffraction-images, whose magnitudes relative to the central image can be calculated in terms of the optical details of the telescope and the elements of the grating ‡   The auxiliary images are, however, really very narrow spectra and, as the interval between successive images depends on the wave-length of the light, we may, so long as the images are not appreciably lengthened, take the observed intervals as a measure of the wave-length of the brightest portion of the star's spectrum, its so-called "effective wave-length"   The chief use of the objective grating has, however, been in the accurate determination of a scale of stellar magnitudes by comparing diffracted images of the brighter stars with the normal images of the fainter stars   Merton § has suggested an application of the coarse grating, when crossed with an objective prism, to the spectrophotometry of stars in regions of the spectrum where the wedge method fails owing to the light being absorbed by the wedge

Entirely different principles underlie two modern stellar photometers which must be briefly described   Considerably increased accuracy was obtained by Stebbins in 1910 when he measured the light from a star by the change in the resistance which the light caused, when it fell on the surface of a selenium cell ‖   This method has given place

* *Conference Astrophotographique Internationale de Juillet* 1900, circular No 8 41 1901

† *A N*, cliv 317, 1901
§ *Proc R S*, xcix A, 78, 1921

‡ *M N R A S* lxxiv 50 1913
‖ *Ap J*, xxxii 185 1910

to the still more refined and accurate method of measuring a star's brightness by the number of electrons emitted from a small cell of metal photo-electrically sensitive to radiation in the visual region, when the light from the star falls on it * The cells of different metals, e g calcium and potassium, are chiefly sensitive to light from different parts of the spectrum This property enables us, by studying the effect of a star's light on cells of different metals, to deduce the relative intensity of radiation in different wave-lengths and hence the effective temperature of the star The question of colour-index is one of the points of contact of photometry with stellar physics proper We shall see later how closely photometry is bound up with one of the most startling recent developments of the subject †

Sampson ‡ has made a very promising application of the photo-electric cell to the measurement of relative intensities of lines in a spectrum and also to the variations of intensity of different portions of the continuous spectrum He passes a beam of light through a spectrogram on to a photo-electric cell, used in the form of a Koch microphotometer, and obtains, clear of personal equation, an accurate measure of the distribution of light with wave-length in the star's spectrum There are photographic and other difficulties to be overcome, but the method promises results of a much higher order of accuracy than those given by earlier methods Still another instrument used for studying

* See *Vierteljahrsschrift der Astronomischen Gesellschaft*, xlviii 210, 1913 (Meyer and Rosenberg) and *A N*, cxcvi 357, 1913 (Guthnick) for early observations *Ap J*, xlv 69 1917 (Kunz) and *M N R A S* lxxix 344, 1919 (Lindemann) and *Lick Obs Bull* No 349, 1921 (Cummings), give theoretical and instrumental details

† For a fuller account of photometers, see ' An Introduction to the Study of Variable Stars ' Caroline Furness (Constable) 1915 also ' Einfuhrung in das Studium der veranderliche Sterne ' K Schiller, Leipzig 1923

‡ *M N R A S*, lxxxiii 174, 1923, and xxxv 212, 1925

stellar radiation is the thermocouple, which was successfully applied to stars by Pfund, in 1913 * Essentially this makes use of the fact that if a circuit consists of two metals, and if the joints are kept at different temperatures, then a current flows through the circuit and a measure of the current allows a determination of the difference of temperatures of the joints A recent account of the construction of vacuum thermocouples has been given by Pettit and S B Nicholson † The thermocouple can be used with coloured screens to determine the distribution of spectral energy across the sun's disc in different wave-lengths It can also be used to measure the total radiation from a spot on the sun or from a star In the latter case, the additional use of a screen, such as a water screen, has led to useful conclusions about the intensities of the infra-red radiations in stellar spectra Coblentz has applied this method to the long-period variable stars ‡

10 (b) Other Instruments for measuring Radiation —The bolometer, a sensitive instrument for measuring the distribution of heat in the solar spectrum, was designed and constructed by Langley, in 1880 § The principle lay in exposing to the source of radiation a small surface, consisting of exceedingly thin strips of platinum This formed an arm of a Wheatstone bridge When warmed by so little as 0 0001° C , the resistance of the surface altered sufficiently to produce a measurable deflection in the needle of a galvanometer in the Wheatstone bridge current In its essentials the instrument was completed by a recording

* *Allegheny Observatory Publications* iii 45 1913
† *Ap J* lv 295 1922 See also Coblentz *Scientific Papers of the Bureau of Standards* No 438 1922
‡ See Chapter XII below
§ *Proceedings of the American Academy of Arts and Sciences,* whole series xvi 342 1881 See also *Professional Papers of the U S Signal Service* No 15 Researches on Solar Heat by S P Langley, 1884

apparatus which showed the deflection of the galvanometer corresponding to a given wave-length in the spectrum   In this way knowledge of the absorption lines in the solar spectrum was extended in the infra-red far beyond the range accessible for study before the bolometer was used   In addition to the bolometer, which gives only relative values for the radiation measured in different wave-lengths, a pyrheliometer is used to determine the absolute scale * This consists of a thermometer attached to a blackened copper disc, which can be exposed to the shade or the sun at will   Good contact between thermometer and disc is secured by an intermediate film of mercury   This is the instrument used by Abbott in his work on the value and variation of the total amount of solar radiation

11 Stellar Interferometer —An instrument has recently been designed at the Mount Wilson Observatory to carry out a suggestion made by Michelson, in 1890 , † the separation of close binary stars and the angular diameters of star discs are now being measured by means of a stellar interferometer   In its essence this consists of an arrangement by means of mirrors at a controlled distance apart (the first stellar interferometer had a base of 20 feet), which secures that two parallel beams from the star are viewed together in an eye-piece   The two light-paths through the instrument for rays from any point on the star-disc are different   There results in general for the whole star-disc an interference pattern in the field of view , the fringes only vanish when the angular diameter of the star-disc is a simple function of the wave-length of the star's light (assumed known), and of the separation of the mirrors An observation of the separation of the mirrors, for which

* See *Annals of the Astrophysical Observatory of the Smithsonian Institution*, ii 36 1908

† *Phil Mag* v ser xxx , 1 1890   *Ap J* li 263 1920 and liii 249, 1921

the fringes vanish, leads to the angular diameter of the stellar disc or the angular separation of the two components of a close binary * The first star disc was measured by Pease in December, 1920, at Mount Wilson The star Betelgeuze (a *Orionis*), was found to have a diameter of 0″ 045 † It is not without interest to note that Michelson's original paper led to the development of the objective grating for stellar work, which has been referred to above

* *Ap J* lvi 40 1922 Merrill gives as the average residual 1° for position angle and 0″ 0007 for separation

† See below § 38

LABORATORY INVESTIGATIONS

12 Relation to Stellar Physics —The problems set to the student of stellar physics are first to identify the lines appearing in celestial spectra, and secondly, from an examination of the grouping, the intensities and the structure of these lines, to deduce something as to the physical condition of the outer layers of the stellar atmospheres   The task of identifying the lines and bands in celestial spectra has been steadily and so successfully faced by a succession of researchers in the laboratory that we may expect confidently that before many years are gone those lines which are still of unknown origin (see Appendix VIII), will have been identified The interpretation of the spectra in terms of physical conditions has, however, only recently been put on a sure footing Until Bohr's theory of atomic spectra was available to guide the investigator, the chief spectroscopic experiments, which seemed to have a bearing on astrophysics, were too scattered in nature to lead to any satisfactory conclusions   Some of these will be selected for mention below, mainly in order to reflect the early history of the laboratory side of astrophysics   But pride of place must be given to recent experiments on the stimulation of spectra and their explanation in terms of Bohr's theory

13 Bohr's Theory —Adopting the Rutherford model for the atom—a central, positively charged nucleus surrounded by a system of electrons rotating about it in certain defined orbits—Bohr postulates that radiation from an atom only

takes place when it changes from one stable or stationary state to another, in which the energy of the atom is less If E_1, E_2 are the values of the energy of the atom in the initial and final stages, then the transition is accompanied by a monochromatic radiation of frequency, ν, given by the equation $h\nu = E_1 - F_2$ (h is a known physical constant called Planck's constant) Similarly, if an atom changes from a condition with energy E_2 to one with energy E_1 it will absorb radiation of frequency ν Each line in the spectrum of an atom corresponds to an energy difference between two possible levels characteristic of the atom. The energy may be drawn from incoming radiation or from the impulse of a colliding electron By bombarding an atom with electrons moving with selected speeds, Franck and Hertz * were able to confirm Bohr's relations between the frequency of the emitted radiation and the change in the energy of the atom, relations based originally on experiments on the photo-electric effect The changes of energy correspond in general to the displacement of an electron from one orbit to another in the atom , in a particular case the electron may be driven from its orbit right out of the atom, which is left singly ionized On the capture of an electron by this ionized atom lines of its typical (or arc) spectrum are emitted, the lines depending on the orbits into which the electron successively in the course of its recapture settles Now the atom may have had two electrons removed or be doubly ionized In this case the capture or binding of one electron will lead to the emission of a different set of spectral lines called the second optical spectrum, the spark spectrum or, in the earlier literature, the enhanced spectrum Similarly, if three (or more) electrons have been lost by the atom, bright lines of the

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* For the chief references see *Phys Zeitsch* , xx 143 1919 See also The Origin of Spectra Foote and Mohler New York, 1922

third optical spectrum (or spectrum of higher order) will be obtained on the binding of an electron by the trebly (or more highly) ionized atom These spectra have been grouped vaguely under the term super-spark spectra The following notations have been adopted for the different classes of spectra corresponding to atoms ionized by the loss of one, two, three, or four electrons If an absorption line is due to the loss of an electron by, or its displacement in, a neutral atom of silicon, then the notation Si or Si I is used to indicate the nature and condition of the atom to which the line corresponds , the same notation is used for an emission line accompanying the capture of an electron by a singly-ionized atom If a line is absorbed by a singly-ionized atom of silicon losing a second electron or having an electron displaced (or emitted by a doubly-ionized atom binding an electron) the notation Si^+ or Si II is used * Similarly, for doubly and trebly ionized atoms we have Si^{++} or Si III , Si^{+++} or Si IV Lines of all these four groups have been identified by A Fowler , all four are present in different stellar spectra The different degree of ionization of the atom may be taken as an indication of the different amount of excitation to which it is subject, and we may trace this excitation in general to thermal radiation The classification of spectral lines into series corresponding to different stages of ionization is, therefore, of fundamental importance in the investigation of stellar temperatures † Of great assistance in this work is the spectroscopic displacement law of Kossel and Sommerfeld ‡ According to this law, the structure of the spectrum of an

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* The notation adopted by Norman Lockyer and other writers—pSi, meaning proto silicon—was applied to all classes of ionized atoms

† For experimental work of this nature having direct application to astrophysics, see A Fowler *Phil Trans* ccxiv A 225 1914 , *Proc R S* , ciii A, 413, 1923

‡ *Berichte d Phys Ges* xxi 240 1919

atom of an element is the same as that of an atom of the following element in the periodic table, the second atom having lost one more electron than the first   Thus the spectra Na I, Mg II, Al III, and Si IV have a common structure, and it is possible to use this fact as an aid in classifying the lines due to the more highly ionized atoms of the last-named elements   Another case of similar spectra is that of H I, He II, which is of considerable historic interest in astrophysics   It was long thought that a series of lines, first found in ζ *Puppis*, were due to hydrogen   It is now definitely established that they are due to ionized helium

14 Thermal Ionization —An important step in the application of Bohr's theory to astrophysics was taken by Saha when he applied * the equations of thermodynamics to the study of the ionization of a stellar atmosphere as a function of its pressure and temperature   Assuming that the ionization of a gas—the dissociation of an atom into a positively charged ion and one or more electrons—is essentially of the same nature as a chemical reaction, he considered a reversible reaction of the type—
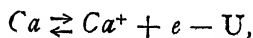
$$Ca \rightleftharpoons Ca^+ + e - U,$$

where Ca, Ca^+, e are gram-molecules of neutral calcium atoms, singly ionized calcium atoms and electrons respectively and U is the work expressed in calories, required to ionize one mol of calcium atoms   Following the methods of physical chemistry,† Saha deduced an equation of the form—

$$\log_{10} \frac{x^2}{1 - x^2} P = - \frac{5050 \, V_1}{T} + 2 5 \log T - S,$$

* *Proc R S*, xcix A 135 1921   *Phil Mag*, xl 472, 809, 1920 , xli 267 1921   xliv 1128 1922   See also Milne *Observatory*, xliv 261 1921   and Russell *Ap J* iv 119 1921

† See Tolman *Jour of the Amer Chem Soc* , xlii 1185, 1920, and xliii 866 1921

where x = the fractional number of the atoms of the gas
which are ionized

P = the total pressure of the gas

V_i = the ionization potential of the gas (i e the potential through which an electron must drop in order to acquire sufficient velocity to ionize an atom with which it collides), measured in volts

T = the absolute temperature of the gas

S = the chemical constant of the electron = 6 69

Saha pointed out how the percentage ionization depended upon the temperature, the partial and total pressures, and the ionization potential of the gas   Without anticipating subsequent discussion unduly, it may be mentioned here that while Bohr's theory alone leads to such general statements as that the lines of a principal series of a neutral atom should steadily fade with increasing temperature while the lines of the principal series of an ionized atom should rise to a maximum and then fade, Saha's theory leads to an understanding of the different types of spectra found in different layers of the Sun's atmosphere, and to an interpretation of the difference of spectra of giant and dwarf stars In his theory fresh emphasis has to be laid upon the ionization potential of the element concerned and on the pressure of the atmosphere in different layers of the same star and in stars of different masses and densities   As a typical instance of the kind of laboratory experiment which Saha's theory at once elucidates, we may cite that of Huggins *
with regard to the lines of calcium, Ca I, 4227 [g], and Ca II, 3933 [K], and 3968 [H]   Huggins found that if a spark was taken between two iron electrodes moistened with a strong solution of calcium chloride, the arc line [g] weakened much more rapidly than the spark lines [H] and [K] when

* *Proc R S* lxi 433 1897

the electrode was washed repeatedly in pure water Huggins's explanation in terms of vapour density is now seen to be consistent with Saha's general interpretation of such phenomena

15 Furnace, Arc, and Spark Spectra —Considerable work has been done in the laboratory during the past forty years in grouping lines according to their relative strength under varying conditions of temperature and electrical excitation This work was of direct value in connection with the identification of lines in stellar spectra, doubtful identifications being frequently settled through reference to other lines which could be identified with more certainty, and which showed similar behaviour in the laboratory The early work on enhanced (spark) lines of metals by Norman Lockyer and his colleagues at South Kensington found important applications in the identification of the lines in such spectra as those of novae in their early stages   Here we may mention the early experiments of Liveing and Dewar* who attempted to study the changes in the spectrum of a heated vapour accompanying controlled changes of temperature and without chemical action   The metal to be studied was vaporized inside a carbon tube which was used as one terminal of an arc   King,† at Bonn, and later at Pasadena, carried out numerous investigations, giving for many elements detailed grouping of the spectral lines which strengthen at different stages of excitation   (Plate 7)

The investigations with the electric furnace extend to temperatures of some 2000° K   In the arc we are concerned with temperatures of about 3100° K   In the spark, though it is difficult to speak of temperature, it is clear that the atoms of the vapour under investigation are subjected to more violent electrical excitation than in the arc. Even in the arc, however, the enhanced lines typical of the

* *Proc R S* xxxiv 123, 1882
† *Ap J* xxi 236, 1905 and later papers in the *Ap J*

PLATE **7**
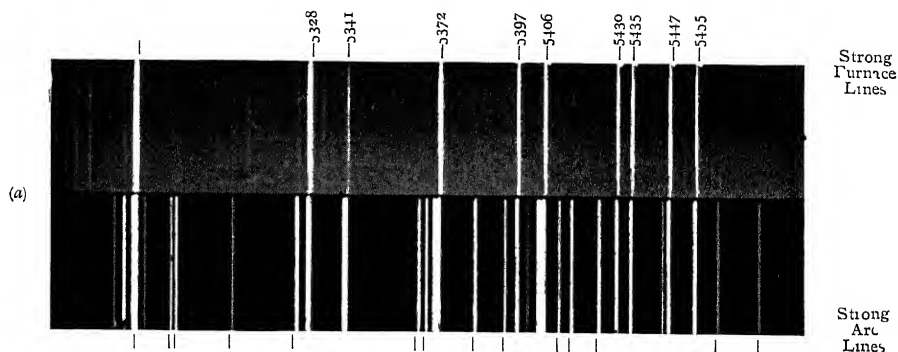
SPECTRUM OF IRON IN ELECTRIC FURNACE AND ELECTRIC ARC

Photographed by C P Butler at National Physical Laboratory 1911

ARC SPECTRUM OF IRON   Photographed at Cambridge
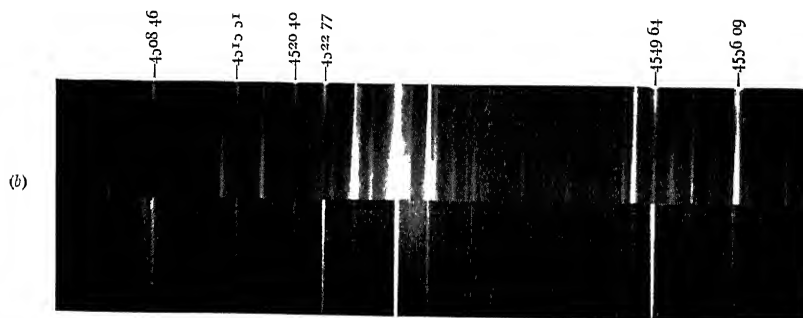
SPARK SPECTRUM OF IRON   Photographed at Solar Physics Observatory London

showing typical enhanced lines

spark spectrum are found in regions of a high potential gradient, e g near the positive pole of a Pfund arc * In varying ways and by different methods the grouping of complicated spectra have been empirically determined The main types of spectra can be paralleled in celestial sources The accurate discussion of the physical condition of the atmospheres, giving rise to these spectra, will become possible as soon as the series relationships of the spectral lines concerned have been established in the laboratory

16. Pressure and Stark Effect —Stark † and Lo Surdo ‡ observed, in 1913, that in a strong electric field lines were split into polarized components So far, no direct instance of Stark effect has been traced in astrophysical spectra It is, however, possible that the broadening of lines under pressure may be an instance of the Stark effect as also the slight shifts of lines in the direction of greater wave-length observed under pressure by Jewell, Mohler, and Humphreys § Strong local electric fields may be set up between atoms close together in the lower layers of a star's atmosphere It has, indeed, been held that the continuous spectrum of a star is to be traced to the complications in a many-lined spectrum caused by the action of strong local electric fields in broadening the separate lines Efforts have been made to elucidate the displacements of lines in the solar spectrum in terms of pressure, but it is now generally held that the pressure in the layer where the absorption lines originate is too low (being of the order of 10^{-1} atmosphere or less) for pressure effects to be measurable There is, however, one effect of pressure which may be reflected in stellar spectra, and that is a change of relative intensity of different lines in

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* Merrill, *Ap J* , lvi 475, 1922   See also Plate 7 (b)

† *Sitz d k Preuss Akad d Wiss* , 1913 p 932

‡ *Atti della Reale Accad dei Lincei, Rendiconti* xxii 2 p 664 1913

§ For references see *Ap J* , vi 169, 1897   lvi 16 1922

a spectrum and a tendency in an emission spectrum for lines of higher term number in a series to reverse A stellar spectrum containing both dark and bright lines of the same spectral series of the same element is suggestive of the spectra found in the laboratory under pressure Though results obtained under high pressures do not apply directly to astrophysics, we have already seen * that low pressures play an important part in Saha's theory

17 Zeeman Effect —The effect of a magnetic field on a spectrum, the discovery of which was announced by Zeeman in 1897,† has, however, important applications in astrophysics Zeeman detected the widening of a line when the source of the spectrum was subject to a strong magnetic field, and was viewed in a direction parallel to the lines of force Lorentz, on theoretical grounds, deduced that the widening was due to the addition of two wing lines which should be circularly polarized in opposite directions to each other, and this result was confirmed in the laboratory The presence of strong magnetic fields in sunspots was first shown by Hale ‡ and connected with vertical currents of charged particles Later he discovered and made a detailed study of the general magnetic field of the sun, showing that it corresponded fairly closely to that of the earth Admitting that the field varies with the depth of the gas examined, one can give an idea of its strength by saying that the vertical field at the poles is about 50 gauss, while that of the earth is 0 6 gauss A typical sunspot field would be about 1000 gauss §

* § 14 above

† *Verslagen der Wis en Natuurkundige Afdeeling d k Akad v Wetenschappen te Amsterdam* vi 13, 1897 also *Phil Mag* , v ser xliii 226 1897

‡ *Ap J* xxviii 315 1908

§ For an account with bibliography of the determination of the sun s general magnetic field, see Seares *Observatory* xlv 310, 1922

18 Chemical Action and Impurities—The presence of the vapour of a separate gas, whether chemically active or not, may very seriously affect a spectrum For instance, the hydrogen spectrum, which plays so considerable a part in the classification of stellar spectra, may be reduced in intensity by one-half by the mere introduction of a small quantity of mercury vapour (one molecule in 2500) * Again, Merton and Nicholson have shown † the different kind of effect on the hydrogen spectrum of mixture with helium They worked with a vacuum tube filled with pure helium at 41 mm pressure When a heavy discharge was passed through the tube a very slight evolution of hydrogen took place from the electrodes which had not been completely cleared of hydrogen Under these conditions, the spectrum of hydrogen predominated, far surpassing the helium lines in brilliance, and the higher members of the important Balmer series of hydrogen lines, so conspicuous in certain celestial spectra and so difficult to reproduce in the laboratory, were seen as well as in any previous experiment Spectra of a mixture of hydrogen and helium under slightly different conditions, but with a larger proportion of hydrogen present, showed the helium spectrum predominant and the hydrogen spectrum greatly reduced in intensity Crew ‡ found that if a metallic arc was struck in an atmosphere of hydrogen instead of in air, those lines which were stronger in the spark spectrum of the metal were strengthened in the arc in hydrogen Hemsalech and de Gramont § have found that the well-known spark line of magnesium λ 4481 can be obtained as a sharp line in a stable arc burning between magnesium electrodes in an atmosphere of nitrogen, with quite low potential gradients They suggest that in

* Lewis, *Ap J* x 152, 1899
† *Proc R S* , xcvi A, 112 1919
‡ *Ap J* , xii 167, 1900
§ *Phil Mag* , vi ser , lxiii 843 1922

this case some special chemical reaction may be the important factor in the result

Another way in which impurities have been shown to affect the presence of enhanced lines in the spectrum of a gas has been demonstrated by King * If the vapour of an easily-ionized substance, such as potassium, is present in an atmosphere of a less easily ionized substance, such as calcium, the supply of electrons is greater in the mixture under given conditions than it would be in the presence of calcium alone The proportion of positively ionized atoms of calcium is diminished in the condition of relative equilibrium and the enhanced spark lines are weakened relatively to the lines of the normal atom Russell has suggested † that this result may account for some puzzling anomalies in astrophysical spectra Royds has shown ‡ that un symmetrical lines may be displaced slightly in the presence of impurities This he also ascribes to changes in the ionization due to the presence of impurities In celestial spectra, one may count confidently on the presence of mixtures of gases, and it follows that the effects of impurities on spectra must have application in many cases

Of chemical action there is not much that need be said. Celestial spectra are generally concerned with high temperatures where the spectra of elements and not of compounds are to be expected Nevertheless, in the solar spectrum, particularly in the spectrum of sunspots, and in the spectra of red stars of low temperature, bands have been observed which are due to compounds Here we need only refer to magnesium hydride, which gives a band spectrum traced by Liveing and Dewar § to the combination of hydrogen and magnesium and identified by A Fowler ‖ in the spectrum

* *Proc N A S* viii 123 1922   † *Ap J*, lv 119 1922
‡ *Kodaikanal Obs Bull* No lxxiii 1923
§ *R S Proc*, xxxii 198, 1881
‖ *Phil. Trans* ccix A 460, 1909

of sunspots, to titanium oxide identified by A Fowler *
in the spectrum of o *Ceti*, to zirconium oxide identified
by Merrill † in the spectrum of S type stars   to the hydro-
carbon band—Fraunhofer's [G] band—identified by Newall,
Baxandall, and Butler in the ordinary solar spectrum, ‡
and to a band due to ammonia found by A Fowler and
Gregory in the sun's ultra-violet spectrum § Carbon com-
pounds have also been traced in the band spectra of comets
and of certain stars, and laboratory work has been necessary
to trace the origins of some of these bands   But the extent
to which the spectra of compounds enter into astrophysics
has been sufficiently indicated, and details can be left for
discussion in the sections where they more naturally belong
In this chapter all that need be added is a reference to
the thermo-chemical discussion of the pressure of a star's
atmosphere in which such a compound as titanium oxide
can be present at a temperature of about 3000° K ‖ The
conclusion is that the partial pressure of the titanium and
oxygen together is of the order of 10^{-4} atmosphere   The
study of the heat of reaction of compounds throws light on
the selection of those found in the cooler stars, those with
the highest heats of formation being the most likely ones
to appear

19 Black Body Radiation—Kirchhoff, in his great
memoir on the ' Relation between the Emissive and Absorp-
tive Power of Bodies for Heat and Light " invented the
term " black body " for a body which, for infinitely small
thickness, absorbs all rays which fall upon it   If a hollow
body is kept heated uniformly and has a small aperture,
the radiation emerging from the aperture approaches that

* *Proc R S* lxxii 219 1904
† *Pub A S P* xxxv 217 1923
‡ *M N R A S*, lxxvi 640, 1915
§ *Phil Trans* ccxviii A 351 1918
‖ Atkinson *M N R A S* lxxxii 396 1922

of a black body more and more closely the smaller the
aperture   The variation of the black body radiation with
the wave-length for different temperatures has been deter-
mined by a combination of thermodynamical theory and
the quantum theory, and has been verified by Coblentz *
and others   The shape of the energy curve and the wave-
length of its maximum have been used † to determine the
temperatures of stars, the assumption being made that the
continuous spectrum is effectively that of a black body
Broadly speaking, the conclusions as to the temperature
of the radiating layer of a star, derived by this method,
may be accepted

* *Scientific Papers of the Bureau of Standards* No 406 1920
† See Chapter VI below

CHAPTER IV

THE SUN

20 The Nature of the Sun —The Sun is a body spherical
in shape and 1,390,000 km in diameter, it lies at an average
distance of nearly 150,000,000 km from the Earth Its
mean density is 1 4, and it contains elements familiar to us
on the Earth Its surface consists of glowing gas at an
absolute temperature of about 6500° K * Storms occur in
its atmosphere represented by gigantic outbursts of flaming
gas above its ordinary surface and by cyclonic whirls below
The rotation of the surface shows a marked equatorial
acceleration Dark spots, which may be large enough to
swallow up the earth many times over, appear in a range
of some 30° of latitude on each side of the equator and with
a frequency which varies in a principal period of $11\frac{1}{8}$ or $22\frac{1}{4}$
years Along with periodic changes in the Sun's spottedness
come changes in its upper atmosphere, and notably in the
tenuous extended atmosphere called the corona, which is only
seen at eclipses The spots are the centres of strong magnetic
fields, and the Sun itself has a general magnetic field resem-
bling that of the Earth

To anticipate later chapters of this book we may add
that different layers of the Sun's atmosphere give spectra
like those of stars of different spectral classes its normal
Fraunhoferic spectrum is of class G, the spectrum of a
higher layer or chromosphere is of class A to F, and that of

* See *Observatory* xlvii 160, 1924

a lower layer or of the sunspots is of class K   The Sun is
a dwarf star, rather fainter than the majority of the stars
we see, and slightly below the average in mass   It is rather
advanced in its evolutionary course, and is at present
probably cooling down   It probably forms part of a local
cluster moving through the galaxy, its own peculiar velocity
being 17 7 km /sec   (See § 45 below as to the exact meaning
of this statement)

The above is a very brief statement of the main details
that we know about the Sun   The rest of this chapter will
be devoted to developing some of the above statements

21 The Reversing Layer —The ordinary absorption
spectrum of the Sun, that of the so-called reversing layer,
was mapped by Fraunhofer in 1814   Subsequently, meas-
urements of the wave-lengths of the lines were made by
Ångström and others, Rowland * publishing, in the years
1895-97, a " Preliminary Table of Solar Spectrum Wave-
Lengths " This covers a range from 2975 A to 7331 A
Outside this range the work has been extended in the infra-
red by Abney † and by Meggers and Brackett to 9850 A ‡

From numerous coincidences with lines in the spectra
of certain elements, these elements can be safely identified
as present in the vapours that give the Sun's absorption
spectrum   The list of elements thus identified slowly grows
The work of identification is not easy   Rowland's Tables
contain some 20,000 lines, and out of these a single element,
e g iron, may account for as many as 2000 lines   Again,
some elements may be present only in compounds   Thus
the laboratory lines associated with pure nitrogen have not
been traced, but lines due to bands of cyanogen and ammonia,
compounds of nitrogen, have been found in very large

* *Ap J* 1 -v 1895-97
† *Phil Trans* clxxvii 457 1885
‡ *Alleghenv Observatory Publications* vi 13 1919 *Ap J* xlvii
I 1918 and lin 121 1921

numbers   Altogether at present the following 66 elements
have been identified in the Sun   They are placed in the
order in which Rowland placed them, according to the
number of lines identified *—the elements after the stroke
have been identified later , they have not all been identified
in the Fraunhoferic spectrum, some, like helium, belonging
only to the upper atmosphere or chromosphere —

<div style="text-align:center">TABLE I</div>

<div style="text-align:center">ELEMENTS IDENTIFIED IN THE SUN</div>

Iron	Barium	Tungsten
Nickel	Aluminium	Indium
Titanium	Cadmium	Bismuth
Manganese	Rhodium	Rubidium
Chromium	Erbium	Dysprosium
Cobalt	Zinc	Gadolinium
Carbon	Copper	Thallium
Vanadium	Silver*	Caesium
Zirconium	Glucinum	Tantalum
Cerium	Germanium	Osmium
Calcium	Tin	Thorium
Scandium	Lead	Lithium
Neodymium	Potassium	Samarium
Lanthanum	———————	Tellurium†
Yttrium	Nitrogen	Platinum†
Niobium	(in compounds)	Uranium†
Molybdenum	Helium	Arsenic†
Palladium	Oxygen	Mercury†
Magnesium	Ruthenium	Praesodymium†
Sodium	Gallium	Thulium†
Silicon	Europium	Terbium†
Hydrogen	Ytterbium	Lutetium†
Strontium	Neo-Ytterbium	

One source of error in identifying elements as present
in the Sun must be briefly mentioned   The dark lines of
the solar spectrum are produced in the passage of rays
from the hot photosphere, which gives a continuous spectrum
through the cooler vapours of the " reversing layer,"
which absorb an appreciable fraction of the radiation of

* *American Journal of Science,* xli 244 1891
† Doubtful identifications

certain definite wave-lengths   But these rays, on their way
to the spectroscope, pass through our atmosphere   How
are we to tell that the absorption is not all produced in and
by the Earth's own atmosphere ?   One answer comes at
once in the differences found in the spectra of different stars
A second answer has been provided by the development of
methods for picking out from the Sun's spectrum the lines
which are due to the absorption of our atmosphere, the so
called telluric lines   One way is to compare the spectrum
of the Sun when high in the heavens—observed especially
from the summit of a high mountain such as Mont Blanc
with the spectrum of the Sun when low down—observed at
sea-level   The difference in the depth of terrestrial atmos
phere through which the light has travelled in the two
cases is sufficient to alter considerably the intensity of the
telluric lines and enables the investigator to pick them out
with confidence   A further check may be supplied by making
use of the Doppler effect *   When a mass of gas is moving
towards the observer, the absorption lines due to it are all
displaced to the violet by an amount which enables the
velocity of the gas relative to the observer in the line of
sight to be measured   when the motion of the gas is away
from the observer the lines are correspondingly displaced
to the red   Now the Sun is rotating on its axis and in
spectra of the east and west limb of the Sun the lines of solar
origin are found displaced to the violet and the red respec
tively, while the telluric lines are unaffected   Hence a
comparison of two solar spectra taken at the east and west
limb will, if the dispersion of the spectrograms is sufficient,
enable the telluric lines to be picked out with certainty

The amount of light available in the solar spectrum
enables an investigator to use a very high dispersion   Work
of very great accuracy can be undertaken   The resultant

* See Chapter VII below

PLATE 8

FLASH SPECTRUM COMPARED WITH FRAUNHOFERIC SPECTRUM
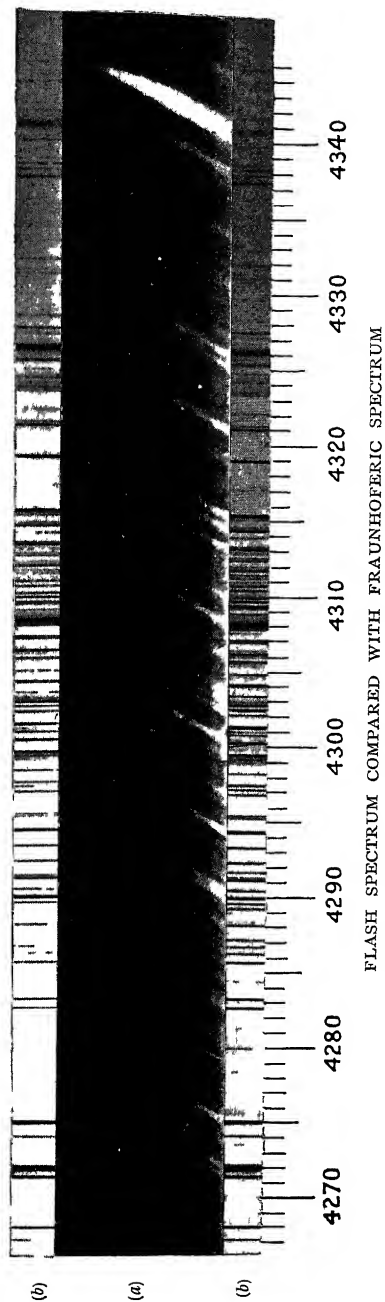
(a) Flash spectrum photographed by H F Newall in Sumatra at the Eclipse of 1901 May 17 18 with a 5 inch plane grating mounted as an objective grating   (b) Rowland s map of the solar spectrum

shift of lines, due to motion, pressure, or other causes, can be measured to an accuracy of 0 0005 A One of the most important tests of the equivalence hypothesis which underlies Einstein's generalized principle of relativity was provided by a predicted shift of the Fraunhofer lines to the red by an amount ranging from 0 008 A at 3790 A, to 0 014 A near the red line Hα The evidence is necessarily bound up with that for currents in the solar atmosphere, and with a determination of the pressure of the gases that give the absorption lines With the general adoption of low values for the pressure of the reversing layer, the controversy over the reality of the Einstein shift of the lines in the Sun's spectrum has ended in its general acceptance *

22 **Higher Layers in the Sun's Atmosphere , Prominences** —The reversing layer of whose composition we have evidence in the Fraunhofer spectrum, extends through several hundred kilometres Above this layer lies the chromosphere, a layer of very bright gas several thousands of kilometres thick, and consisting principally, at the highest levels at any rate, of hydrogen and calcium This layer has been studied almost entirely at total solar eclipses It gives the so-called " flash spectrum " (Plate 8) At the beginning or end of totality, when the Moon just covers the photosphere, part of the chromosphere is left projecting as an arc of varying depth—a greater depth being necessarily visible at the centre of the arc than at the cusps If this arc is photographed through a prismatic camera, the resulting spectrum consists of a number of bright arcs—one corresponding to each line in the spectrum of the glowing gas of the chromosphere—and the length of the arc seen grows with the height to which the gas which gives the corresponding line extends upward in the chromosphere The flash spectrum is, for its lower levels, a reversal of the Fraunhofer spectrum,

* See *Observatory*, xlvii 9, 1924

but certain lines, notably the Balmer series of hydrogen, the lines of helium and the enhanced spark lines of certain metals are strengthened considerably and show arcs of increased length, showing that they come from gases which extend to higher levels in the chromosphere   Helium was, in fact, first discovered in the chromosphere, and only subsequently identified by Ramsay in the laboratory

The most complete list of chromospheric lines was obtained by Mitchell at the eclipse of 1905 *   Mitchell gives the intensities of these lines and also, from a measure of the lengths of the arcs corresponding to the various lines, a statement of the height in the sun's atmosphere to which the gas producing each line extends   The vapours of ionized calcium, hydrogen, helium, and various ionized metals extend, in that order, highest above the Sun's limb , the Ca II lines [H] and [K], reach a height of 14,000 km , $H\beta$ and $H\gamma$ a height of 8000 km , and the He line [D_3] a height of 7500 km   The presence of lines due to the ionized atoms of certain metals has been discussed by Saha † in terms of his application of the thermo-chemical Reaction-Isobar to ionization considered as a case of dissociation The degree of ionization for any element for a given temperature and pressure is determined by the theory, and on examination of the solar evidence it is found that pressure plays a very important part in determining the relative ionization of the different elements in the high-level chromosphere   The first application of Saha's theory was, in fact, made to the chromosphere, though the theory was subsequently developed and applied successfully to general stellar physics

Rising out from the chromosphere are the prominences, clouds of flaming gas lying quietly above the chromosphere, or bursting outwards with a high velocity and falling back

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* Ap J., xxxviii 407 1913   See also Dyson, $Phil$ $Trans$, ccvi. A 403 1906

† $Phil$ Mag , ser vi xl 472 1920   See § 14 above

PLATE 9

LARGE SOLAR PROMINENCE

Photographed by A S Eddington at Principe at the Eclipse of 1919 May 29   The prominence
extended from the east point on the solar equator to 40° S

again on to the Sun's surface (Plate 9)   At first these, too, were only seen at eclipses, but Lockyer and Janssen independently showed, in 1868, that they could be observed at any time *   As they consist mostly of glowing hydrogen gas it was only necessary to use a spectroscope with rather a wide slit and to observe the spectrum of the limb of the Sun at the red line Hα   Setting the slit parallel to the limb, the bright line from the prominence could be easily seen against the faint continuous spectrum of the sky background Hence the height of a prominence at any point of the limb could be measured—or rather the height of the section of a prominence shown by the slit   If the slit was not wide enough to show the whole prominence successive observations at different distances from the same point on the limb enabled the observer to build up a picture of the whole prominence   Hydrogen, helium, and calcium are the principal elements found in the prominences   The heights of these prominences vary between some hundreds to some hundreds of thousands of kilometres   The quiescent prominences generally consist of hydrogen only   The eruptive prominences often contain also metallic vapours As their name implies, they suggest the action of some explosive forces   Prominences have been followed to a height of 830,000 km above the Sun's surface , †   at such great heights they usually show as bright clouds broken clear from the links which, at first, connect them to the solar disc   The present evidence about the velocities with which these eruptive prominences rise from the Sun's limb well justifies the use of the word eruptive   The velocity seems to remain constant for a considerable time, and

* *C R*, 26th Oct, 1868   The idea of the method was due to Lockyer   Janssen was the first to apply it successfully   His success and Lockyer s were announced at the same meeting of the Académie des Sciences

† *Ap J*, liii 310, O J Lee

then suddenly to increase The discontinuity in the upward velocity may be observed more than once in the growth of a prominence, and suggests a series of internal explosions or the sudden passage from one layer of the solar atmosphere to another of lower density showing less resistance to motion

The principle employed by Lockyer and Janssen in building up pictures of prominences underlay the development of the spectroheliograph (see Chapter II above), which, in the hands of Hale, has added so much to our knowledge of the Sun's upper atmosphere It had been known from Young's visual observations that the dark [H] and [K] lines of calcium were sometimes brightly reversed in the neighbourhood of spots The spectroheliograph, which enables the Sun's disc to be photographed in monochromatic light, was first successfully applied to the photography of the luminous calcium clouds or flocculi and, in fact, to the distribution of the calcium vapours over the whole disc (Plate 10) (Naturally, it also gave a simple means of photographing the prominences in light of a given suitable wave-length in full sunlight) The spectroheliograph also led to a more detailed knowledge than the simple distribution of bright calcium clouds over the disc Deslandres pointed out that the structure of the calcium lines [H] and [K] was complex On a broad, dark line [K$_1$], there was superposed a bright, central portion [K$_2$], which was again crossed by a narrow, central, dark line [K$_3$] * Now, laboratory results † support Deslandres' view that these three portions [K$_1$], [K$_2$], and [K$_3$] belong to vapours of diminishing density and, therefore, presumably to vapours at increasing heights If, then, using a large dispersion, we set the second slit of the spectro-heliograph to catch the light in turn from [K$_1$], [K$_2$], or [K$_3$] only, we

* [K$_2$] has been found in 12 stars also and [K$_3$] in 2 stars see § 60 below

† Huggins *Proc R S*, lxi 433, 1897

can get pictures of the Sun in the light from ionized calcium
vapours at three different heights of the Sun's atmosphere
corresponding to the reversing layer, the chromosphere
and the prominences These pictures differ considerably,
notably in the neighbourhood of spots and prominences
(Plate 10) Special attention has been paid by Deslandres
at Meudon to the upper layers, both of the hydrogen and
calcium vapours, and to the dark filaments which spectro-
heliograms show in these upper layers—high masses of
hydrogen or calcium gas which, on the limb, are seen as
prominences (Plates 11 12 See also, Plate 15) By
means of the *spectro-enregistreur des vitesses* or velocity
recorder (see § 7 above), he has also inquired into the up
and down velocities of these higher vapours and their
relation to the general circulation in the Sun's atmosphere
(Plate 13) One more general remark has to be made about
the spectroheliograph pictures While the calcium flocculi
given by [K_2] are bright, the hydrogen flocculi are, in
general, dark,* resembling more the [K_3] filaments (Plate 14)

23 Corona—Stretching far beyond the chromosphere
and prominences, extending, it may be, thirteen million
kilometres from the limb or even more, there may be seen,
at times of total eclipse, a pearl coloured atmosphere
This is known as the corona The total light given by it
is about half that of the full moon † The shape of the
corona depends upon whether the Sun is near a maximum
or minimum phase of spot-frequency (see § 25 below) At
spot minimum there are to be seen near the Sun's poles,
short, fine rays or streamers, while broad bands of light

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* For an account of Hale's work with the spectroheliograph see
' The Study of Stellar Evolution, ' by G E Hale (Chicago 1909)
Also *Publications of Mt Wilson Observatory passim* Deslandres
work is given in *Annales de l Observatoire d Astronomie Physique de
Paris sis Parc de Meudon,* Tome iv 1910
† Kunz and Stebbins *Ap J* xlix 151, 1919

sweep out from the equatorial regions to a much greater distance Neither set of streamers is radial nor straight, and the boundary between the two sets is well defined, generally about 30° from the poles At spot-maximum the distribution of the streamers round the disc is much more uniform, and the corona does not extend so far in any direction as the equatorial portions of the minimum corona (Plate 15)

The spectrum of the corona is a blend of several types There is a continuous spectrum with dark absorption lines probably due to reflected sunlight—polarization tests support the view that a large portion of the coronal light is scattered solar light   There are also, in the lower layers, a number of bright lines due to some unknown element or elements—presumably gases in a state of extreme tenuity. J W Nicholson showed that the wave-lengths of the lines of this spectrum could be connected together by a set of simple numerical relations * He deduced them from the dynamical vibrations of two model atoms with nuclear charges of $+ 5e$ and $+ 7e$, which he called protofluorine and coronium respectively In his theory, the nucleus of the atom is surrounded by a single ring of electrons each of charge $- e$ rotating round the nucleus The periods of transverse vibrations of such an atom were examined by Nicholson, and he obtained a very simple formula relating them to one another Series of lines were obtained, such that the cube roots of the wave-lengths in any one series formed an arithmetical progression, while the wave-lengths of members of one series were in a constant ratio to those of the corresponding members of others   Thus,

$$(5303\ 3)^{\frac{1}{3}} - (4359\ 0)^{\frac{1}{3}} = (4359\ 0)^{\frac{1}{3}} - (3534\ 0)^{\frac{1}{3}} = (3534{\cdot}0)^{\frac{1}{3}}$$
$$- (2820)^{\frac{1}{3}} = 1\ 103$$

* $M\ N\ R\ A\ S$ lxxii 1911, and lxxvi 1916

PLATE 14

(a)

(b)

(c)

(d)
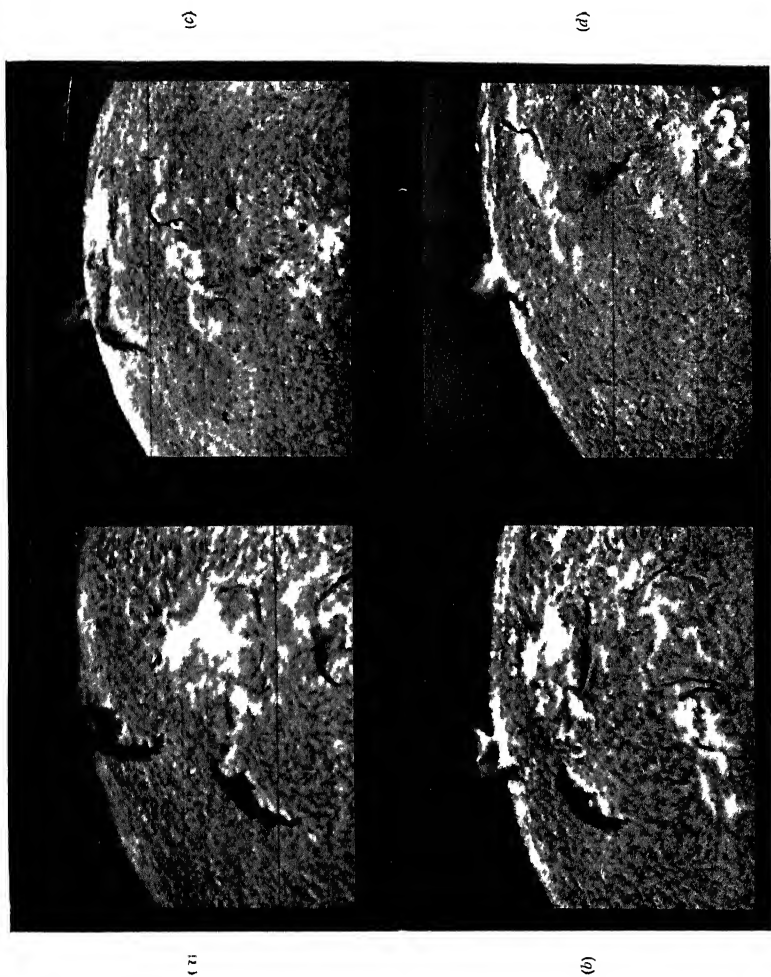
SPECTROHELIOGRAMS (WITH THE SECOND SLIT IN THE CENTRE OF THE Hα LINE) OF
THE WESTERN LIMB OF THE SUN

Obtained by F Ellerman on (a) June 27 (b) June 28 (c) June 29 (d) June 30 1917 with the 13 foot spectroheliograph of
the Mount Wilson Observatory They illustrate how the hydrogen prominences projected dark on the disc become bright
on the limb

PLATE 15
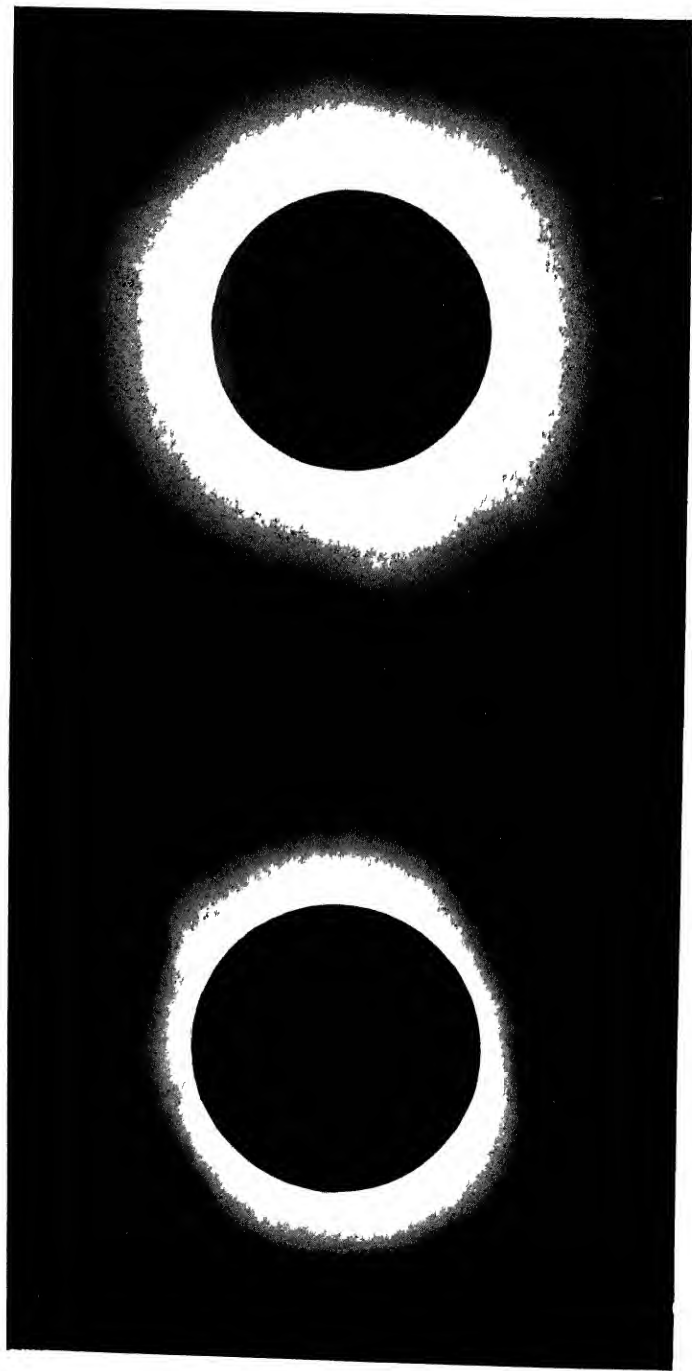
PHOTOGRAPHS OF THE CORONA (a) AT MINIMUM (b) AT MAXIMUM

(a) Photograph by H. F. Newall in Sumatra at the eclipse of 1901 May 17 18   (b) Photograph by H. F. Newall at Guelma at the eclipse of 1905 August 30

The lines 5303 3, 4359 0, 3534 0 were known lines, the line 2820 is too far in the ultra-violet to be observed   However, it fits into Nicholson's scheme of the coronal wave-lengths for the two known lines 4566 0, 3642 5 should form part of a second series of lines whose wave-lengths are in a constant ratio to the above series, and we have

$$\frac{4566\ 0}{3534\ 0} = \frac{3642\ 5}{2820\ 0} = 1\ 292$$

Or, again, we have

$$(3891)^{\frac{1}{3}} - (3602\ 3)^{\frac{1}{3}} = (3602\ 3)^{\frac{1}{3}} - (3328\ 2)^{\frac{1}{3}} = 0\ 399$$

and $(5535\ 8)^{\frac{1}{3}} - (5117\ 7)^{\frac{1}{3}} = (5117\ 7)^{\frac{1}{3}} - (4722)^{\frac{1}{3}} = 0\ 457$

while

$$\frac{3602\ 3}{5535\ 8} = \frac{3328\ 2}{5117\ 7} = 0\ 6508$$

Nicholson's investigation was made at a time when Bohr's theory of atomic spectra, that radiation could not come from mere dynamical vibrations in the atom, was in process of being established   Hence, although his series relations tied up the whole of the known coronal spectrum into two families of lines, his work has been generally overlooked by physicists   That the series relationships represent something real, even though the models from which they were derived may have to be abandoned, was strikingly confirmed at the eclipse of 1914 by the discovery in the coronal spectrum of a new line in the red at 6374 5*   This line fitted into the first of the above-mentioned series since

$$(6374\ 5)^{\frac{1}{3}} - (5303\ 3)^{\frac{1}{3}} = 1\ 103$$

These series, for which $\lambda = a\ (n + \mu)^3$ where n is an integer, remain isolated, not paralleled by any laboratory spectral series   The key to the physical conditions of their appearance has not yet been found

* C R clix 791, 1914, and see § 65 below

4

24 Sunspots—In 1610 Galileo discovered by the aid of the newly-invented telescope the presence of dark spots on the Sun's surface Though naked-eye spots had been recorded in China for some 1400 years this discovery, new to Western minds, was received at first with hostile incredulity , it was, however, confirmed in due course, and the sunspots have proved a fruitful source of information as to the Sun The spectrum of the spot differs from that of the Fraunhoferic spectrum The presence of bands, due to compounds, such as magnesium hydride, and the increased strength of certain low-temperature arc lines, such as those of vanadium, suggest that the spot is at a lower temperature than the reversing layer * The sunspot spectrum is the same as that of the stellar class Ko, while the Fraunhoferic spectrum is of class Go Frequently broad absorption lines are found reversed over spots indicating the presence of hot masses of prominence matter above the spot This presence of prominences over certain spots can be verified by examining the limb of the Sun as the spot reaches it Evershed,† by spectroscopic observation of spots well away from the Sun's central meridian, discovered that at lower levels the spot umbra showed a flow out from the centre along the disc St John confirmed this, and amplified the result by showing ‡ that there was an inward flow at the higher levels, and that the difference of velocity of flow at different levels provided a means of plumbing the depth of the solar atmosphere and of deciding at what depth individual absorption lines originated These discussions of level for different lines agree with the changes in the magnetic field in a sunspot at varying depths, with the corresponding spectroscopic values

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* For a discussion of the lines affected in sunspots, see W Mitchell *Ap J* xxii 4 1905
† *M N R A S*, lxix 454 1909 and lxx 217, 1910
‡ *Ap J* xxxvii 322 and xxxviii 341 1913
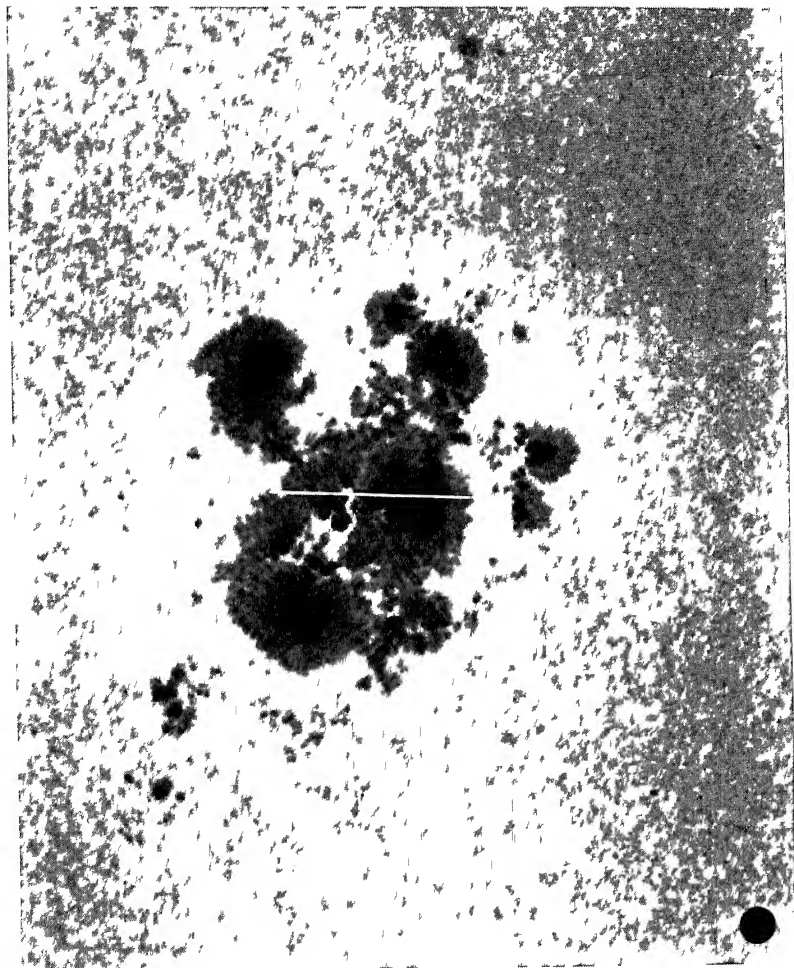
PLATE 16

GREAT SUN SPOT GROUP, 1917, AUGUST 8

Photographed at Mount Wilson Solar Observatory   The disc in lower left hand corner represents the relative size of the Earth   The white line gives the position of the slit used for Plate_17

PLATE 17

(a) (b) (c) (f)
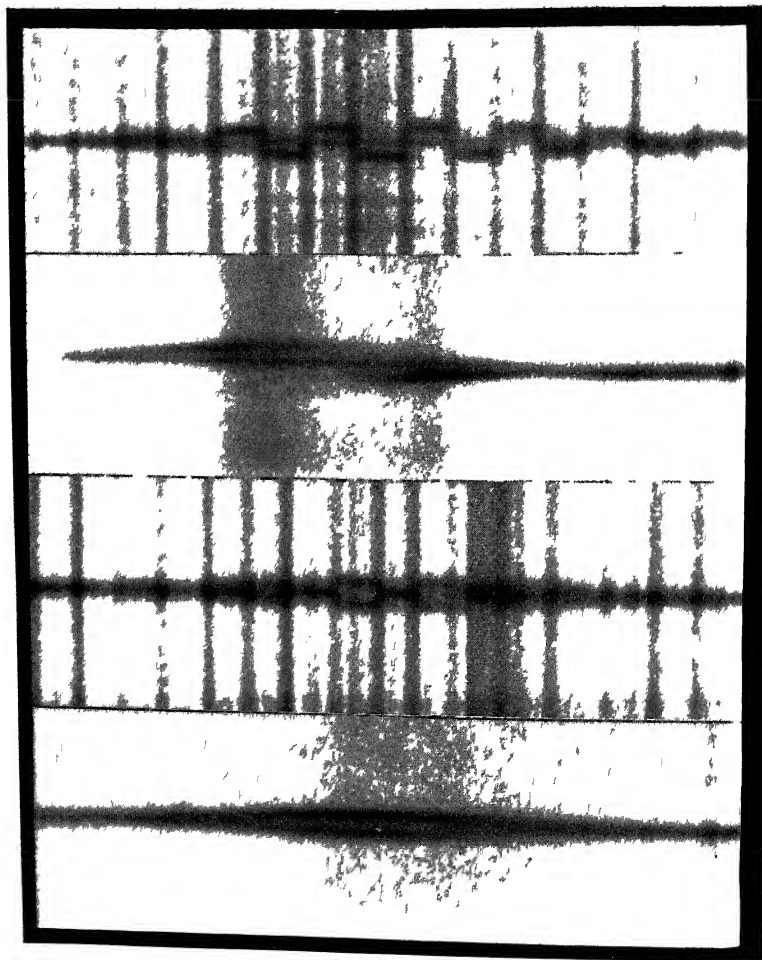
IRON TRIPLET AT 6173 Å

In spectrum of spot indicated by white line in Plate 16 showing reversal of circular y polarized light, (a) and (b) plane polarized light of spot near Sun's limb taken with nicol and (a = single b = compound) half wave plate (c) and (f) circularly polarized light of spot near centre of Sun taken with nicol and (f = single d = compound) quarter wave plate

for the solar rotation and with the relative intensities of the lines, weaker lines originating from lower levels

It had been long known that a general broadening of lines was characteristic of sunspot spectra   It was Hale, who, in 1908,* discovered that one of the chief factors in producing this broadening was this presence of a strong magnetic field in the sunspot   Polarized components, such as Zeeman had found in the laboratory, were shown by means of a nicol prism to form part of the broadened lines   Observations pointed to a magnetic field in the spot radial to the Sun and increasing with the depth (Plates 16, 17)   The magnitude of the field—running up to 3000 gauss in exceptional cases—and its polarity have been examined for many spots   The magnetic fields have also been used by Hale † for the detection of spots not found by the ordinary photographic methods   Local magnetic fields have been detected by their Zeeman effect, and it has become possible to trace the life-history of a spot or spot group through a longer period than had hitherto been possible from visual or photographic observations alone   The magnetic fields in spots have been attributed to the vortical motion of negatively-charged particles , this explanation is suggested by pictures of spots obtained with the spectroheliograph   The polarity of the spot fields exhibits some unexplained phenomena , two or three facts of importance stand out   There is a very strong tendency for leading spots of groups in the northern and southern hemispheres of the Sun to show opposite polarity   again, spots occurring in pairs, as they do quite commonly, show in general opposite polarity, the polarity of the western or leading spot agreeing in general with that of single spots in the same hemisphere   It is as though the spots are the open ends of a vortex filament lying mainly inside the Sun   It

* *Ap J* , xxviii 315 1908
† *Proc N A S* viii 168 1922   *M N R A S* lxxxii 168 1922

is probably a fact of prime importance that at the spot-minimum of 1912 it was found that the general polarity of the leading spots in the northern and southern hemispheres changed sign * After 1912 the normal polarity of the leading spot in the northern hemisphere corresponded to that of the northern magnetic pole of the Earth No change of polarity occurred at the following maximum, but at the minimum of 1923 a second change of polarity was discovered † If, as seems likely, a general change of polarity occurs at each minimum, we may have a valuable clue towards the explanation of some of the puzzling phenomena of solar periodicity

Hale ‡ has suggested that a suitable classification of spots would be in terms of the number of spots in a group and their magnetic polarity The double or bipolar spot in which we have two principal spots of opposite polarity, the leader representing the normal polarity for its own hemisphere, is the commonest type of spot There may be a stream of small spots joining them and these, normally but by no means always, show the same polarity as the nearest larger spot The " trailer " or following spot tends to be further from the Sun's equator than the leader , this tendency increasing with the latitude In addition many spots appear to be unipolar, that is, they consist of single spots or groups of small spots with the same magnetic polarity Some of these show small companions of opposite polarity, thus linking on to the ordinary bipolar systems A further study of magnetic fields in the neighbourhood of unipolar spots may well reveal that they are essentially like the bipolar spots, only some disturbing cause has masked the one end of the vortex from appearing as a visible spot In this connection a study of the changes

* *Ap J* xlix 174, 1919
† Hale *Proc N A S* , x 53 1924
‡ *Ap J* xlix 170 1919

in the strength of the magnetic field of a spot before and after its birth and during its subsequent growth and decay should give very valuable information as to the formation of Sun spots   Fox * has examined the differential motion of the calcium flocculi which always surround spot areas He finds evidence of rotary motion round the spots, but no simple connection with the observed polarity of the magnetic fields of the spots   For the period 1903-8 he found that about single spots and the following members of bipolar spots the motion was anti-cyclonic, i e opposite in sense to the rotation of the Sun on its axis   The motion was cyclonic about preceding members of bipolar spots

Spot groups are generally inclined to the equator, the leading or westernmost spot being nearest to the equator   The inclination of the axis of the group to the equator increases regularly with the latitude   This alignment of the spot groups must be connected with the equatorial acceleration in the Sun's rotation (see § 26 below)   Butler † has discussed the position of the axes of elongated patches of calcium flocculi   He finds a similar tendency for them to be inclined equatorward to the west in both the northern and southern hemispheres

25 Periodicity —That the outermost layers of the Sun undergo marked changes from time to time has been mentioned above in the paragraph on the corona   These changes are correlated with much more easily examined variations in the proportion of the solar surface that is covered by spots   It was Schwabe of Dessau who, by counting the number of spots, first made it clear that the spot frequency fluctuated regularly in a period of about 10 years ‡

* *Pub of the Yerkes Observatory*, iii 162 1921
† *M N R A S* , lxxxii 334 1922   lxxxiv 134 1924
‡ *A N* , xx 283, 1843

Wolf and Wolfer, of Zurich, investigated the early sun-spot records and derived a value for the main period of $11\frac{1}{9}$ years   Wolfer's table, brought up to date, is given below, in Appendix VII   Subsequent work and data have led to the revised value of $11\frac{1}{8}$ years   Careful analysis of the data suggests subsidiary periods, of which the most important are $33\frac{1}{3}$, 8 36, and 4 76 years   The principal periods are, apparently, all sub-multiples of the longest period, $33\frac{1}{3}$ years   A bold attempt was made by Turner to connect this with the period of the Leonid meteors , though his evidence was not conclusive the suggestion, which originated with Sir John Herschel, that we must look outside rather than inside the Sun for an explanation of its periodicity must be borne in mind as possible   Phenomena such as the varying brightness of Encke's comet at different returns and magnetic disturbances on the Earth indicate that phenomena at points remote from the Sun are, at any rate, closely correlated with the solar periodicity

In each hemisphere, after a minimum, the spots first reappear in high latitudes—in belts about 30° from the equator—and steadily appear nearer to the equator as the maximum approaches , the northern hemisphere becomes active before the southern hemisphere   The outburst dies out as the latitude of the spots reaches an average value of about 8°   Though the zone where spots are appearing moves during the cycle towards the equator individual spots do not drift towards the equator   There is some evidence, however, that individual bright faculæ actually move away from the solar equator *   The rise to a maximum of spotted-ness is more rapid than the subsequent fall to minimum, the rise taking about 4 years and the fall 7 years   Changes in the distribution of the prominences in latitude accompany the solar period, the relative frequency of prominences in

* *M N R A S* lxxxv 191 1924

high latitudes increasing towards a solar maximum   The corresponding changes in the form of the corona have been mentioned in § 23 above

Very closely connected with the sunspot frequency are curves for the fluctuations of the terrestrial magnetic elements—the intensity of the Earth's field increasing with the spot frequency   Some connection, the exact nature of which is not known, also exists between disturbances on the Sun and magnetic storms and auroræ on the Earth The chief point of interest lies in the recurrence of magnetic storms after an interval of 27 3 days—the synodic period of the spot zones   it is as though a storm arises when the Earth enters a beam of charged particles coming from a particular point on the Sun and is repeated 27 3 days later when the Earth occupies effectively the same position relative to the Sun

26 Solar Rotation —The Sun's surface does not rotate with the same angular velocity in all latitudes, nor do different layers in the same latitude rotate with the same velocity   As is also the case for Jupiter, there is an equatorial acceleration in the rotation of the Sun, the speed of angular rotation increasing as the latitude decreases   The high-level lines show the most rapid rotation for any given latitude and at the same time they show the least equatorial acceleration   Thus Adams found from the Hα line that the daily angular velocity for high-level hydrogen was 15 0° at the equator, and 14 6° at latitude 30° *   For the reversing layer he got corresponding values 14 5° and 13 7° and for spots the values are 14 4° and 13 7° The simplest expression for the daily angular velocity in terms of the latitude ϕ, appears to be of the form $a + b \cos^2 \phi$, this form is due to Faye, though Carrington

* Adams,   An Investigation of the Rotation Period of the Sun," *Carnegie Institution Paper* No 138, 1911

first derived from observations an approximate law, his law involving sin $\frac{7}{4}\phi$ * The law in use is empirical, and its form is unexplained as, in fact, is the equatorial acceleration itself It is by no means certain that the coefficients a and b in the formula are constant even for a given depth and for given lines in the spectrum As already stated, they differ for different levels of the solar atmosphere A tabular statement for all determinations has been given by Fox, † from his tables the following average results for the daily motion may be derived —

Hα	$13° 6 + 1° 4 \cos^2 \phi$
Faculæ and flocculi	$11° 9 + 2° 6 \cos^2 \phi$
Sunspots	$11° 6 + 2° 8 \cos^2 \phi$
Reversing layer	$11° 0 + 3° 2 \cos^2 \phi$

Newall has suggested ‡ that a reason why solar activity after a minimum recommences in middle latitudes and spreads towards the equator is to be found in turbulence arising from the velocity gradient in latitude At low and high latitudes the velocity gradient is low The retardation accompanying turbulence would increase the difference between the motion of a layer and of the neighbouring layer on the side towards the equator, and hence the tendency for the disturbance and its accompanying vortices to spread towards the equator

27 Magnetic Field of the Sun —As in the case of the Earth, the Sun has a general magnetic field which resembles roughly that of a uniformly magnetized sphere This field, though small, being of the order of 20 gauss, has been detected and measured § Its origin is unknown , there are

* ' Observation of the Spots on the Sun R C Carrington, 1863

† *Pub Yerkes Observatory* iii Part III 1921

‡ *M N R A S*, lxxxii 104 1921

§ For an account of this work and a good bibliography see Seares, *Observatory* xliii 310 1920

difficulties in the way of attributing it to the convection of electric charge   enormous electric fields in and near the Sun would be required, and these must be ruled out   The polarity of the field is in the same sense as that of the Earth, the magnetic north pole being near the Sun's northern pole of rotation

The Sun's magnetic axis makes an angle of 6° with its axis of rotation   The magnetic field is only measurable through a very thin shell of the Sun's atmosphere, and in that shell, as in the case of sunspots, it increases with depth, the value ranging from about 10 to about 50 gauss in a depth of 200 km

28 Temperature and Radiation —The radiation from the Sun has been exhaustively studied in order to fix the temperature of the Sun   The two main lines of study have been a quantitative study of the total integrated radiation, and a qualitative examination of the distribution of radiation, particularly of the wave-length of maximum radiation   Corrections have to be very carefully worked out to allow for the absorption of the Earth's atmosphere   When these corrections have been applied it is found that the Sun does not radiate exactly like the laboratory black-body * by comparison with which its temperature is to be decided   It follows naturally that different methods of determining its temperature give different results   Wilsing's figures † may be given as typical of them   For the photosphere he estimated that the absolute temperature varied from 5400° K for the upper layers, to 7000° K for the lowest layer from which radiation reached us   As a round figure, 6500° K may be remembered as representing the Sun's surface temperature. Of the temperature at any considerable depth we know nothing at all certain, although it is safe to assert that it

* See § 34 below
† *Potsdam Pub* xxiii No 72, 1917

is higher, and in all probability it is very much higher than in the photosphere

The black-body temperature given by light from the centre of the Sun's disc is higher than that given by light from the darkened limb At the centre where we view the Sun in the direction of its radius the radiation comes from a greater average depth than at the limb It is of greater intensity, especially in the light of shorter wave-lengths, and the ratio limb/centre examined for different wave-lengths shows that the temperature of the surface which we see at the limb is some 15 to 20 per cent lower than that of the mean depth to which we see at the Sun's centre

A study of the Sun's radiation and absorption spectrum leads to the following description of the solar atmosphere * The gases of the chromosphere are held up by radiation pressure acting on individual atoms, the pressure at the base of this deep layer being of the order of 10^{-7} atmosphere At the bottom of the chromosphere gravity becomes predominant in deciding equilibrium, there is a rapid increase of pressure with depth This is the reversing layer which is at an average temperature of $5000°$ K In quite a short distance, 200 to 300 km , the pressure increases to about 10^{-2} atmosphere, the opacity increases rapidly, and we pass to the opaque photosphere, the transition being rapid enough to give the observed sharp limb of the Sun St John has gone further and drawn up a tentative scheme involving not only pressures at different depths but also the accompanying circulation in the Sun's atmosphere †

The best measure of the radiation received by the Earth from the Sun is the following if a surface of one square centimetre is exposed outside the Earth's atmosphere perpendicular to the Sun's rays and at the Earth's mean distance

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* Russell and Stewart *Ap J* , lix 208, 1924
† *Ibid* , lx 39 1924

from the Sun, then enough radiant energy from the Sun
would cross it in a minute to raise the temperature of a
gramme of water by about 1° 94 Centigrade   This figure
is called the solar constant

Abbott, who has done the most recent work * on this
question at several stations maintained by the Smithsonian
Institution of Washington, found that the solar radiation
varied slightly from causes lying outside the Earth's atmos-
phere   In his view the Sun is a variable star with small,
irregular fluctuations in its radiation, due, possibly, to solar
radiation being unequal in different directions   A study by
Guthnick † of the reflected light received from the planet
Saturn failed to confirm Abbot's result   But Abbott, with
the aid of observations at two stations (Mount Harqua
Hala, Arizona, and Montezuma, Chile), over a period of a
year, confirmed the variation of the Sun's radiation ‡ and
added the following general rules connecting this variation
with changes on the Sun's surface   The value of the solar
constant increases with increased sunspot activity, as
evidenced by the formation of new spots and the growth
of spots, though it may drop when a sunspot group crosses
the central diameter of the Sun's disc   The value of the
solar constant declines steadily in a long quiescent period
of solar activity

* See *Annals of the Astrophysical Observatory of the Smithsonian
Institution*, iv 1922

† *A N*   ccv 113, 1917

‡ *Report on the Astrophysical Observatory of the Smithsonian
Institution for* 1923, 109   See also *Proc N A S* ix 194 1923

THE SOLAR SYSTEM

29 The Aurora —The existence of a connection between solar disturbances and the earth's magnetic field was mentioned in the previous chapter An examination of the phenomena of magnetic storms confirms the view based on other observations that there is an ionized layer in the upper atmosphere of the earth Variations in this ionization are supposed to be due to charged particles coming from outside, and presumably for the most part from the sun The most obvious sign of this lies in the luminosity produced in the aurora The delicate draperies, consisting of straight-line streamers ending on the lower side in sharp, bright boundaries are what might be expected if we had ionized clouds of gas coming into the earth's atmosphere along paths determined, in part, by the earth's magnetic field

Auroral streamers have been traced up to heights of 600 km , but the height of the lower boundaries—generally 85 to 160 km *—is of more importance to us For, if the auroræ are, as seems most probable, caused by penetrating beams of charged particles, then we may learn something of the density and constitution of the upper atmosphere from the distance to which the beams penetrate Lindemann† has deduced from the auroræ that there is very little hydrogen present in the auroral regions and that the predominant gas there is helium with a small admixture of nitrogen The spectrum of the aurora certainly shows no sign of hydrogen,

* Wright *Observations on the Aurora* 30 1921
† *Phil Mag* , xxxviii 680 1919

but it does give the negative band spectrum of nitrogen *
As is to be expected from the assumed cause of the auroral
luminosity, the gases whose presence is revealed by spectro-
scopic analysis of the auroral light are the gases of our own
atmosphere

The most prominent line generally in the auroral
spectrum is a line of unknown origin in the yellow-green
at 5577 350 I A †   The rest of the spectrum was found by
Rayleigh ‡ to consist of the negative-band spectrum of
nitrogen, the strongest bands being at λλ3914, 4278   Vegard §
adds three unknown lines at λλ4182 5, 3432 7, and 3208 3
The auroral line can always be found on spectrograms
obtained on plates exposed to the night sky   Campbell first
noted this fact and Slipher found the line on every one of
a hundred plates exposed in latitude 35° N in the course
of three and a half years   The spectrographic evidence,
then, is clear that there is a permanent aurora contributing
towards the light of the night sky

Rayleigh, working with a lens of great light-gathering
power and with a small dispersion, has found in the spectrum
of the night sky, in addition to the principal auroral line, two
faint lines or bands of unknown origin at approximately
λλ4210, 4435 ‖   These bands are probably to be connected
with the aurora rather than with the light which comes
from the meteoric or cosmical dust in the solar system which
we see in the plane of the earth's orbit as the Zodiacal light
Present evidence points to this dust shining merely by
reflected light from the sun

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* Vegard *Phys Zeit* xiv 680 1913
† H D Babcock *Ap J*, lvii 218, 1923   McLennan and Shrum
have identified a sharp line at this wave-length in a mixture of
oxygen and helium (*Nature* cxv 382 1925)
‡ *Proc R S* c A, 367, 1921 and ci A 114 1922
§ *Phil Mag*, xlvi 193, 1923
‖ *Proc R S*, ciii A 45 1923

30 Comets —The expulsion of matter from the sun suggested by the phenomena of auroræ and of magnetic storms brings to mind at once the tails of comets where we have visible evidence of matter in motion away from the sun   A comet consists essentially of a hazy cloud or head of faintly shining matter which usually contracts as the comet approaches the sun   As the head contracts, one or more bright nuclei generally form near its centre and a luminous tail of extreme tenuity streams out from the head in the direction away from the sun   The tail may be accompanied by envelopes on the same side of the comet's head as the sun, and in some cases * the comet may develop a whole series of envelopes as its nucleus passes through stages of alternating activity and quiescence (Plate 18). From the shape of the tail it is possible to calculate the ratio of the gravitational attraction to the repulsive force from the sun   Schwarzschild † and Nicholson ‡ have shown that if the tail consists of particles whose linear dimensions are of the same order as the mean wave-length of the incident light, then the pressure of solar radiation is competent to produce tails of the shapes observed   On the other hand, the velocity of matter in the tails of comets has been determined from the motion of nuclei in individual tails , these give much larger velocities than those suggested by the shapes of the tails and indicate repulsive forces of a higher order than could be given by radiation pressure   still more violent repulsions are required if the envelopes which form between the head of a comet and the sun are formed of matter expelled from the head towards the sun and driven back by the solar repulsion   The forms of the envelopes and the motions of individual nuclei in the tails present real diffi-

* Notably Comet Morehouse (1908c), *M N R A S*, lxix 52, 1908

† *Sitz d Math Phys Classe zu Munchen* 1901 2 193
‡ *M N R A S*, lxx 544 1910

PLATE 18
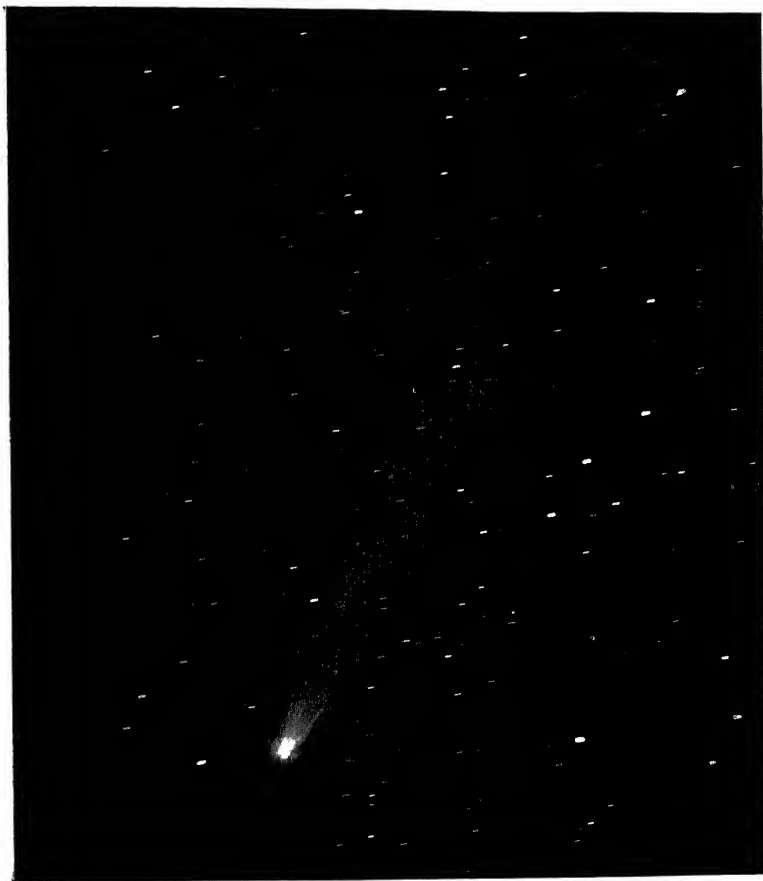
COMET MOREHOUSE, 1908*c*

Photographed with the 30 inch Reflector at the Royal Observatory Greenwich 1908
October 30 6 h 37 m G M T

culties in the way of accepting the pressure of solar radiation as the sole factor in the repulsion of the matter which forms the tail, though it may well be one of the chief factors present

It is permissible to suppose that the very tenuous gas shining in a comet's tail is illuminated by the passage of charged particles issuing either from the head of the comet or from the sun   The spectroscope shows that part of the light is reflected sunlight but that bright bands are super imposed, indicating the emission of light from the comet itself   Donati first noted these bands in 1864,* and Huggins † identified three bands in the spectrum of the head of Comet II, 1868, with three bands which he had found in examining the spectrum of certain compounds of carbon   These bands, with heads at $\lambda\lambda 5635$, 5165, 4737, form part of the " Swan " spectrum ‡ for the hydrocarbons, acetylene and methylene   Other bands of the " Swan " spectrum found in the heads of comets are at $\lambda\lambda 4365$, 4371, 4382, 4685, 4698, 4715   The presence of nitrogen in the head of a comet was indicated later by the cyanogen band at $\lambda 3883$, and the negative band at $\lambda 3914$, sodium was identified by bright [D] lines, and iron also by some of the Fraunhofer lines which appeared bright in the spectrum of the nucleus of the great comet of 1882 §   Sodium has been found in the nucleus of other comets, notably the daylight comet, 1910a, and Comet Wells, 1882a The metallic lines are strengthened and the carbon bands weakened when the comet is close to the sun   The spectrum of the *head* of Comet Wells contained a series of unknown bright bands at $\lambda\lambda 4253$, 4412, 4507, 4634, 4769 ‖ and did not contain the ordinary

* *M N R A S* , xxv 114, 1864
† *Phil Trans* clviii 529 1868
‡ *Transactions of the Royal Society of Edinburgh* xxi 411 1856
§ *Copernicus* ii 237, 1882
‖ Huggins, *Proc R S* , xxxiv 148 1882

hydrocarbon or cyanogen bands   The head of Comet Brooks, 1911c, also contained some unknown bands at $\lambda\lambda$3985, 4000, 4024, 4050, 4073, 4102, 4138   Another series of bands which were observed at $\lambda\lambda$4002-22, 4255-75, 4548-70, 4690-4715 in the *tails* of Comet Daniel, 1907d, and of Comet Morehouse, 1908c, have been traced by Fowler * to carbon monoxide   The tails consisted mostly of carbon monoxide, though cyanogen was possibly also present, sodium found strong in the nucleus was identified in the envelope, and possibly in the tail close up to the head † It is of some interest that Merton has found these carbon-monoxide bands in helium vacuum tubes when only a small trace of carbon is present as an impurity ‡

31 Meteors —The nature of the gas in a comet's tail is known   The source of this gas is less certain   It may be gas that has been occluded by the solid particles or lumps, which form the head, during the passage of the comet in the outer regions of the solar system or in some primitive heated condition   If a comet, after disintegration, crosses the earth's atmosphere, a shower of meteors is observed, believed to be due to collision of the earth with some of the remains of the comet   It is, perhaps, significant that the meteorites which have fallen to earth are generally full of occluded hydrogen, helium, and carbonic oxides   The spectrum of a meteor has been occasionally observed   The Balmer series of hydrogen lines were found by E C Pickering § and the sodium line by v Konkoly ‖   Both of these are probably due to the atmosphere   The spectra of many meteoritic bodies have been determined   For the most part the bodies are composed of iron, nickel, cobalt, and chromium, but magnesium, sodium, calcium, silicon, among common ele

* *M N R A S* lxx 176, 484, 1910
† Newall, *M N R A S*, lxx 460, 1910
‡ *Phil Trans* ccxxii 386 1922
§ *Ap J*, vi 461, 1897
‖ *M N R A S*, xxxiv 82 1873

ments, and gallium and rubidium, among rare terrestrial elements, have also been found *

32 Planetary Bodies —The applications of the spectroscope to the chief bodies of the solar system are not numerous Modifications of the solar spectrum by extra absorption bands, not yet identified, should, in time, throw light on the constitution of the atmosphere of Jupiter, Saturn, Uranus, and Neptune   In the case of Mars there has been a lively dispute, mainly between two schools of American astronomers, on the question whether deviations of the spectrum from the solar spectrum prove the presence of water-vapour in the Martian atmosphere   This dispute is not yet settled, and further work is required to decide whether the spectrum of Mars gives any indication of the presence of water-vapour in the Martian atmosphere St John and S B Nicholson have done preliminary work in the application of the powerful instruments of Mount Wilson to problems of planetary spectra   They have found that the spectrum of Venus gives no measurable evidence either of oxygen or of water-vapour in the atmosphere of Venus, though the investigation should have given positive results if in the double passage through the atmosphere of Venus to the surface (or to the effective reflecting layer) and back again the light had traversed the equivalent of 1 m of oxygen or of 1 mm of precipitable water-vapour †   The possibility of clouds high in the planetary atmosphere acting as the reflecting layer prevents this experiment from being finally decisive as to the atmosphere of Venus

If Mars and Venus show little or no trace of atmospheric absorption in their spectra, the same cannot be said of the major planets   On the red side of Hβ they all show striking differences from the solar spectrum, strong absorption

* See *Ap J* vi 221, 229, 1897   and *Spectroscopic Comparison of Metals South Kensington*, 1907
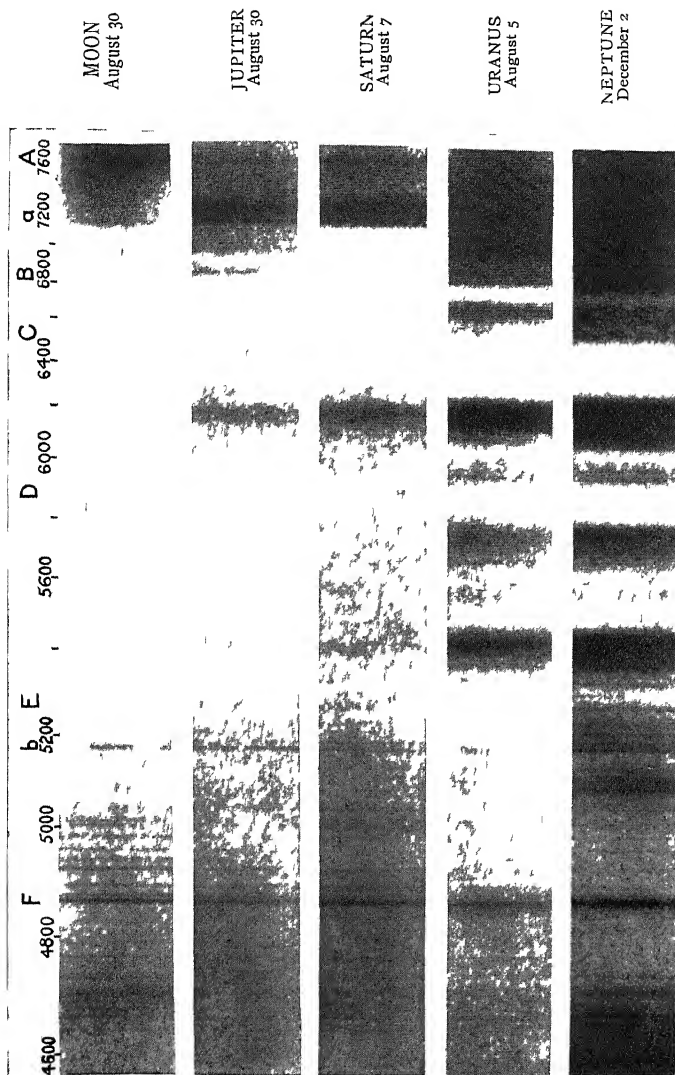† *Ap J* , lvi 380, 1922

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bands of unknown origin appearing in their spectra *
(Plate 19)   These unknown bands strengthen considerably
and become more numerous for Uranus and still more for
Neptune than for Jupiter and Saturn   The obvious sugges-
tion that they are due to absorption by gases lying in inter-
planetary space is negatived by the fact that the rings of
Saturn do not share the strong new bands shown in the
spectrum of the ball   These new bands are presumably
due to the sunlight having penetrated into the atmospheres
of the planets before reflection   The hydrogen lines Hα
and Hβ are both notably strengthened in Uranus and
Neptune, but as Hγ and Hδ are not similarly affected this
may be due to coincidence with other bands   The principal
unknown bands in the planetary spectra are at $\lambda\lambda 5093$,
5428, 5762, 5973, 6191, 6677, 6812, 7022, 7195, 7260   An
identification of these with the absorption bands of chloro-
phyll has been suggested, but the evidence is not conclusive

Keeler,† and later V M Slipher (Plate 20), applied the
spectroscope to study the velocity of rotation of the planet
Saturn and its rings, verifying the view of Maxwell as to the
constitution of the rings and confirming the observed visual
rate of rotation of the planet   This method has been
applied to other planets whose rates of rotation could not
be obtained by watching fixed markings rotate   Thus for
Uranus, Lowell and V M Slipher found that the period
of rotation of the planet was 10 h 50 m , and that the
axis of rotation was normal to the plane of the satellites ‡
The equator is closely parallel to the plane containing the
satellites and the rotation is in the same direction as that
of the satellites, i e it is retrograde   The problem of the
rotation period of Mercury, Venus, and Neptune has not
yet been solved

* V M Slipher *Lowell Obs Bull* , No 42, 1909
† *Ap J* , 1 416 1895
‡ *Lowell Obs Bull* , 53 1912

PLATE 19

MOON
August 30

JUPITER
August 30

SATURN
August 7

URANUS
August 5

NEPTUNE
December 2

THE SPECTRA OF THE MAJOR PLANETS

Photographed in 1907 by V M Slipher at Lowell Observatory Flagstaff Arizona

PLATE 20
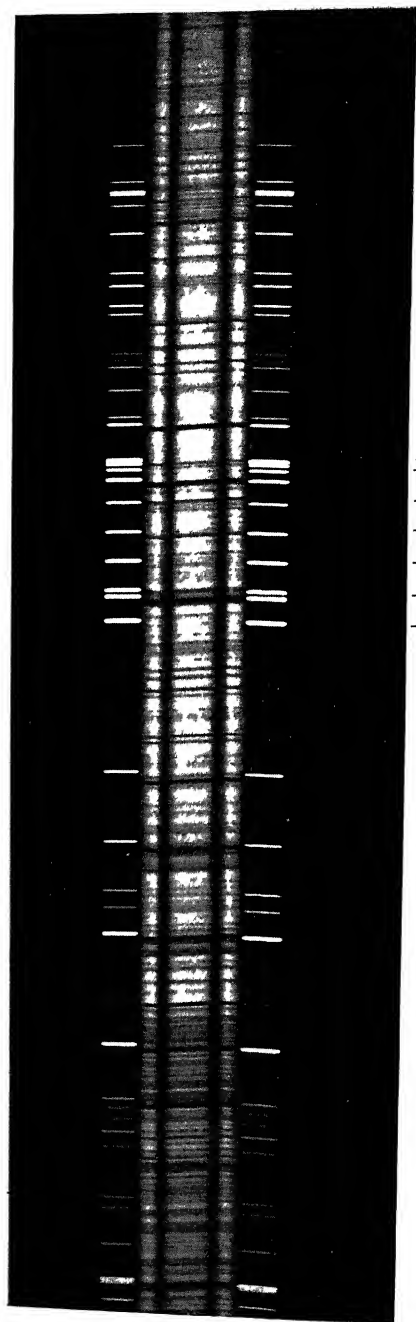
SPECTRUM OF SATURN

Photographed by V. M. Slipher at the Lowell Observatory. The slit was placed over the major axis of the ring system. The slant of the line from the ball shows the axial rotation of Saturn and the reverse slant of the lines from the rings shows that the linear velocity is less for the outer edge of the ring system than for the inner edge. The comparison spectrum is an iron and vanadium arc.

In connection with the gaseous atmospheres, that the spectroscope reveals on the major planets, there must be mentioned the high albedo or reflecting power for light incident on the planets   Russell* gives 0 59, 0 56, 0 63, 0 63, 0 73 as the visual albedos of Venus, Jupiter, Saturn, Uranus, and Neptune respectively, as compared with 0 073, 0 154 for the moon and Mars   The high albedo goes with reflection from cloud surfaces, the low values with reflection from rocks through little or no atmosphere   The albedo of the earth, 0 44, is intermediate between those of the cloudy and cloudless planets

The spectrum of Venus has been used by Evershed in the study of the relativity shift of the spectral lines   His idea was to study the integrated sunlight from a portion of the solar surface not facing the earth so as to eliminate in the determination of wave-lengths any earth-effect on the circulation in the solar atmosphere

Lastly, we may mention the attempt to study the petrography of the moon's surface by photography through colour screens which only admit light from a narrow range of spectrum   R W Wood † and Miethe and Seegert ‡ have taken lunar photographs through different screens, noting the different colours of various portions of the moon's surface , on comparing his plates with photographs of various volcanic ejecta and igneous rocks, Wood suggested that sulphur is present in the dark spot near Aristarchus Most of these applications of the spectroscope and allied instruments to the solar system are incomplete, the astronomer's fancy having been captured by the larger problems awaiting investigation in the stellar universe   It may not be amiss to remind ourselves that there are problems nearer home still awaiting solution

* *Ap J*   xliii   173   1916   † *Ibid* , xxxvi   75   1912
‡ *A N* , clxxxviii   9, 239, 371, 1911

STELLAR RADIATION

33 Stellar Magnitudes —The *magnitude, m,* of a star is a measure of its *apparent* brightness   If a star's distance is known its apparent brightness may be transformed into its absolute brightness by reducing the observed brightness to the value that would be found if the star were a given fixed distance from the earth   The distance chosen for the measure of the *absolute* magnitude, M, of a star is 10 parsecs,* and the relation between M, *m,* and a star's parallax, π, (measured in seconds of arc) is $M = m + 5 + 5 \log_{10} \pi$

The relation between a star's measured brightness, I, and its apparent magnitude, *m,* is given by the equation

$$- 0 \ 4 \ (m - m_0) = \log_{10} I - \log_{10} I_0$$

The zero for the scale is, of course, arbitrary   Here it will be sufficient to say that the limit of visibility for average unaided eyesight is magnitude 6 0, and that the sun's apparent magnitude at a distance of 149,600,000 kilometres has been estimated at $- 26^m 72$, corresponding to an absolute magnitude of $4^m 85$ †   The present normal scale was first given by Pogson, in 1854, after considerable work had been done by Dawes, Herschel, Johnson, and others, in securing a uniform scale of magnitude   Pogson's value

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* A *parsec* is the distance at which the radius of the earth s orbit subtends an angle of 1 second of arc   it is approximately 308×10^{11} kilometres   1 *parsec* = 3 26 light-years

† *Ap J* , xliii 105 1916

for the ratio of the amount of light from a star of any magni-
tude to that from a star of one magnitude fainter was 2 512 *

There is a fundamental difficulty in measuring accurately
even the apparent brightness of a star   The light received
by the observer may have been measured by an eye or by
a photographic plate   The eye and the photographic plate
are chiefly sensitive to different portions of the spectrum,
and photographic plates prepared with different emulsions
differ in their sensitiveness from one another   Again, the
selective absorption of the atmosphere, the glass of the
telescopic objective, or the silvered surface of the reflector
adds a further complication in the determination of the
stellar brightness   It is not to be wondered at that the
different scales prepared at Gottingen, Greenwich, Harvard,
Potsdam, the Cape, Mount Wilson, and Yerkes Observatories
have to be reconciled to one another by corrections depend-
ing on the magnitudes, and on the colours of the stars   At
the Rome meeting of the International Astronomical Union,
1922, Professor Seares presented the report of the Committee
on Stellar Photometry,† giving for a number of stars near
the North Pole the best recent determination of their photo-
graphic and photovisual magnitudes, and also of their colour-
indices   The report also gives the corrections required to
convert the magnitude scales determined at the different
observatories to the standard scale adopted by the Inter-
national Astronomical Union   [The colour-index of a star
is the difference between its photographic and visual
or photovisual ‡ magnitude , colour-index = photographic

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* *Radcliffe Observations* xv 16, 1856

† *Trans I A U* 1 69 1922

‡ The photovisual magnitude is the magnitude determined photo-
graphically on an isochromatic plate exposed behind a yellow filter
giving results approximately agreeing with those obtained from eye-
observations   The standard plate and filter for this purpose have
not yet been fixed by international agreement

magnitude minus visual or photovisual magnitude (see § 36 below)]

34 Black-Body Radiation and Effective Temperature. — The problem of determining the temperature of the stars was first attacked by an application of the second law of thermodynamics   We cannot yet secure in the laboratory artificial sources of heat which are directly comparable with stellar photospheres   We must either reduce the stellar radiation by the intervention of suitable reflecting mirrors and absorbing media before making the comparison * with laboratory results, or we must extrapolate by the laws of radiation, from observations of bodies of lower temperature, to the observed distribution of the continuous radiation in the spectrum of the stars   The whole subject is complicated by questions such as the selective absorption of the light, coming in from the star by the earth's atmosphere and the optical train   There is further, an underlying assumption that the light analysed is purely a temperature radiation and obeys in its distribution the laws of thermodynamics for such radiation   This would be true if the star were a mass of gas at a uniform temperature, if there were no scattering of radiation, and if every part radiated as it would in a steady state   The presence of temperature gradients in the star, the difference of transparency of the outer layers for different parts of the spectrum, the absorption lines in the spectrum and gaseous scattering in the stellar atmosphere all tend to cause departures from the black-body spectrum   The fact remains that the star's continuous spectrum does approximate to that of a black body, and a study of its distribution does give a reasonable guide to the temperature of the star at the average depth from which the emerging radiation comes   This temperature, the black-body temperature most nearly corresponding in amount and composition to the radiation emerging from the star, is called the effective temperature of the star

* See Wilsing, *Potsdam Pub* No 76, 1920

All that need be said here as to the distribution of radiation from a black body at temperature T is that if E_λ is the intensity of radiation corresponding to wave-length λ, $E_\lambda = \dfrac{F(\lambda T)}{\lambda^5}$, where the function F has a form determined by experiment   The wave-length λ_m for which E_λ is a maximum, is related to T by the relation $\lambda_m T =$ constant, i e as T increases the wave-length of maximum radiation moves towards shorter wave-lengths   Also the maximum intensity E_{λ_m} varies as T^5

35 Stellar Temperatures —We pass to the application of these results to stellar problems   The first study of the energy distribution in stellar spectra was a comparison of the relative brightness of a star's spectrum at a number of selected wave-lengths clear of strong absorption lines

Planck's formula of radiation—$E_\lambda \propto \lambda^{-5}\left(e^{\frac{c}{\lambda T}} - 1\right)^{-1}$, where c is the velocity of light—was used to determine the value of T that most clearly fitted the observations of any particular star   The early work of Wilsing, Scheiner, and Munch at Potsdam was visual,* as also was that of Nordmann,† who used a number of coloured screens in his heterochrome photometer   Rosenberg ‡ made a photographic study of the same problem by a method which also involved a comparison of the density of a spectrogram at a number of different parts of the spectrum   Coblentz,§ using a vacuum thermo-couple and a series of transmission screens, has also studied the energy distribution in stellar spectra and derived a temperature scale for the stars   H H Plaskett,‖ by the

* *Potsdam Pub*, xix No 56, 1909, xxiv No 74 1919

† *C R* cxlix 557 1038, 1909, clxxiii 72 1921   *Bull Ast*, xxvi 9, 167, 1909

‡ *Abh d K Leop Karol Deutschen Akad der Naturforschen zu Halle* ci 65 1914

§ *Proc N A S*, viii 49 1922   ‖ *Pub D A O*, ii 213 1923

use of a neutral tint wedge, placed in front of the spectro-scope slit, has studied the distribution of intensity along the whole range of the photographed spectra of stars, and Jules Baillaud * has also studied the distribution of energy by comparing the stellar spectrum with a series of strips of graduated density taken on the same plates as the stellar spectrum, with which they are compared

Sampson has published † a preliminary study of stellar temperatures based on the measurement of the density of stellar spectrograms along the whole range of the photo-graphed spectra His method is to pass a spectrogram across the slit of a photometer and to record the effect of a standard beam of light passing through the spectrogram and falling on a photo-electric cell (Plate 21)   This investi-gation gives the most sensitive results so far obtained for a detailed study of the continuous spectrum of a star   There are photographic and other instrumental difficulties to be met, but the method makes it easy to deal with the whole range of the spectrum with an accuracy and sensitiveness far beyond that of the human eye, and it is likely to become the standard method of stellar spectro-photometry

For the hottest stars higher temperatures than those deduced by Wilsing, Coblentz, and Sampson have been indi-cated by another attack on the problem of stellar tempera-tures initiated by Saha ‡ The fundamental ideas of Saha's theory are   (1) that in stellar atmospheres the ionization of a gas—the dissociation of its atoms into positively charged ions by the loss of one or more electrons—depends upon its temperature, its pressure and the nature of the gas and of the other gases with which it is mixed , (2) that the presence or absence of certain series of lines in the stellar spectrum indicates the condition of ionization of the gas concerned—
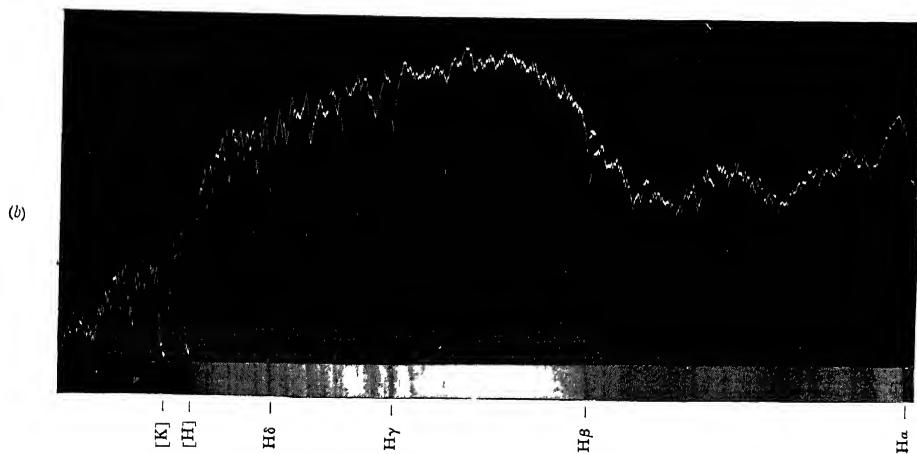
* *Ann de l Obs de Paris* xxx 1914   *C R* clxxvii 424 1924
† *M N R A S* lxxxiii 174 1923   xxxv 212 1925
‡ For references see § 14 above

PLATE 21
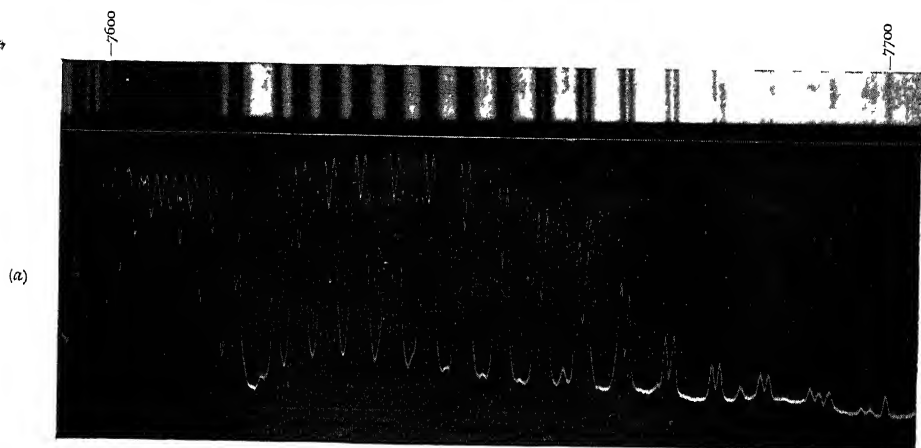
(a) SOLAR SPECTRUM, RECION INCLUDING FRAUNHOFER'S [A] LINE

(b) POLARIS, F8, SPECTRUM OBTAINED WITH AN OBJECTIVE PRISM AND A
6 INCH PHOTOVISUAL LENS

Spectrophotograms taken by R A Sampson at the Royal Observatory Edinburgh

some lines only appearing when a sufficiently large proportion of the atoms are ionized (by the loss of one, two, or three electrons) and some lines disappearing only when practically all the atoms of the element are ionized An examination of the spectra of different elements in a stellar spectrum leads to a knowledge of the condition of ionization of the corresponding gases in the absorbing layer of the star With certain assumptions as to the pressure of the gas, theory enables us to deduce its temperature Saha assumed that the mean partial vapour pressure of an element in that layer of a stellar atmosphere, which contributed to certain absorption lines, lay between $1\,0$ and $0\,1$ of an atmosphere This value of the pressure is now known to be too high, and the resulting temperature scale for the various spectral types derived by Saha has, conse quently, to be modified

R H Fowler and Milne,[*] arguing from the difficulty of deciding the reasons for the marginal appearance or disappearance of a line, have modified the applications of Saha's theory to stellar temperatures by determining the conditions which govern the appearance of given absorption lines at maximum intensity Assuming that the maximum concentration of atoms suitably excited coincides with the maximum intensity of the corresponding lines this maximum concentration is theoretically connected with the ionization, pressure, and temperature of the stellar atmospheres Comparing the evidence from different elements with the known probable temperatures of the stars where certain lines are strongest, they have obtained strong converging evidence that the pressures concerned are of the order of 10^{-4} atmosphere The resulting scale of temperatures covers a wider range than the original scale of Saha The determination of the highest temperatures is complicated

[*] $M\,N\,R\,A\,S$ lxxxiii 403 1923 lxxxiv 499 1924

by the presence of bright lines in the spectra and cannot yet be considered as settled

The following table gives the conclusions as to stellar temperatures derived by the afore-mentioned methods

TABLE II

STELLAR TEMPERATURES

Spectral Type	Wilsing	Nordmann	Rosenberg	Coblentz	Sampson	Plaskett	Saha	R H Fowler and Milne
O5	—	—	—	—	—	—	(Oa)23,000	>35,000
Bo	12 300	—	30 000	13 500	25 000	15 000	18 000	26 500
B1	—	27,700	—	—	—	—	—	19 000
B2	11 450	22 000	18 000	—	20 000	—	—	16,500
B5	10,250	—	12,000	9,500	13,100	—	14 000	—
Ao	9 000	14 000	9 000	8 000	10 700	—	12,000	10 000
A5	7 950	—	7 850	—	8 900	—	—	—
Fo	6,880	7,000	6,930	6,500	7,400	9 000	9 000	7 500
F5	—	—	—	—	—	—	—	—
Go	5,980	—	6 000	6 000	6 200	{6 000 to 5,500}	7 000	6 000
G5	5 250	—	5 200	—	5 100		—	5 300
Ko	4,570	5,000	4,570	—	4 200	{5,500 to 5 000}	—	4,500
K5	4,000	3,600	3,840	—	3 500	—	—	3,900
Mo	3,550	3,100	3,580	3,300	3,400	—	5,000	3,000

The values originally obtained by Wilsing and his colleagues were modified in subsequent investigations   For his work and that of Rosenberg, the tables derived by Brill * from a comparative study of their data have been used

36 Colour-Index —Closely connected with the determination of the wave-length of maximum radiation of a star is the question of its colour-index   Owing to the difference in colour-sensitiveness between the eye and the ordinary photographic plate, different scales of magnitude have been found for stars of different types   The colour-index of a star is the difference, photographic magnitude minus visual or photovisual magnitude   The purely visual magnitudes dependent on the colour perception of an individual observer are being replaced by photovisual magnitudes depending on photography through a suitable yellow filter on to isochromatic plates   But, even so, the optical conditions for determining a standard photovisual scale have not been decided   Both in photographic and in photovisual work, each instrument introduces its own disturbing factor   A scale for photographic work down to magnitude 20 has been adopted by the International Astronomical Union, and a list of magnitudes of stars near the North Pole has been published by the same body †   This is available for all observers and instruments in the northern hemisphere   A final photovisual scale has not yet been adopted, though one has been given by Seares at Mount Wilson which is not likely to have systematic errors of more than a few hundredths of a magnitude   The colour-index is naturally a function of the star's spectrum   The exact connection between the two will depend on the standard scale adopted   Though no final table is yet available, the general run is well shown in the figures used in the Harvard catalogue ‡

* *A N*, ccxix 356, 365 1923   † *Trans I A U*, 1 69 1922
‡ *Harvard Annals*, lxxx 151, 1917

and derived from investigations at Harvard, the Cape, Gottingen, and Yerkes The colour indices of the classes Bo, Ao, Fo, Go, Ko, and M, are given as − 0 24, 0 00 + 0 28 + 0 56 + 1 00, and + 1 35 respectively This scale should really only be applied to dwarf stars Giant stars, especially for types Go to K5, are redder than dwarf stars of the same type and have colour-indices that are greater than the above scale by as much as 0 5 *

The above scale of colour-indices corresponds to two standard mean wave-lengths, λ_{v_o}, λ_{p_o}, used in comparing two given sets of photovisual and photographic magnitudes The adjustment to 0 00 for Ao dwarfs and 1 00 for Ko dwarfs is conventional, and applies to these two standard wave-lengths The reduction of any other set of colour-indices to this scale is equivalent to a change from the λ_i, λ_p used in this other investigation to the standard values λ_{v_o}, λ_{p_o}, to which the standard scale refers

37 Effective Wave-Length —A quantity which has been used along with the colour-index as a simple substitute for accurate spectrophotometry in the case of the fainter stars is the effective wave-length † This is the wave-length obtained from the separation of successive images of the star when a coarse grating is placed over the objective of the telescope (see § 10 (a) above) As with the colour-index, there is naturally a close correlation between the spectral type and the effective wave-length of a star The effective wave-lengths are dependent on observational and instrumental conditions, and no definite standard scale has yet been adopted, but Davidson and Martin ‡ have given the following table connecting effective wave-lengths and spectral types For convenience of reference the Harvard

* Seares, *Pub A S P* xxxiv 56 1922
† See Bergstrand *Nova Acta R Soc Scient Upsaliensis* (ser IV), u No 4 1909 and Hertzsprung *Potsdam Pub* xxii No 63, 1911
‡ *M N R A S* , lxxxiv 430 1924

colour-index and R H Fowler and Milne's temperatures are
repeated in the same table

TABLE III

EFFECTIVE WAVE LENGTH AND COLOUR INDEX

Spectral Type	Effective Wave length	Colour Index	Temperature
Bo	4105	— 0 24	26 500° K
B5	4186	— 0 12	——
Ao	4250	0 00	10 000
A5	4270	+ 0 14	——
Fo	4278	+ 0 28	7 500
F5	4292	+ 0 42	——
Go	4320	+ 0 56	6,000
G5	4396	+ 0 78	5 300
Ko	4474	+ 1 00	4 500
K5	4540	+ 1 18	3 900
Mo	4580	+ 1 35	3 000

38 Stellar Diameters —An interesting application of
the black-body theory of stellar radiation was made by
Hertzsprung * From the knowledge of a star's effective
temperature a value for the surface intensity of the out-
going radiation can be derived The radiation received by
the observer from the star is equal to the surface intensity
multiplied by the solid angle subtended at the observer
The radiation received is measured by the star's apparent
magnitude, the sun, a star of known angular diameter and
of known surface intensity, providing the constant neces-
sary to complete the equation Observation of a star's
apparent magnitude and of its temperature are sufficient,
then, to give a determination of the solid angle it subtends
or, more simply, of its angular diameter Nordmann,†

* *Zeitschrift fur wissenschaftliche Photographie*, iv 43, 1906
† *C R* , clii 73, 1911

Wilsing,[*] Eddington,[†] Russell,[‡] and Bottlinger[§] have, in this way, formed estimates of the angular diameters of certain stars. The simplest formula used is the one adopted by Hertzsprung who has calculated the angular semi-diameter, ρ, for 734 stars[||]. If $T°$ is the absolute temperature of a star, and m its visual magnitude then

$$5 \log \sin \rho = -43.44 + 2.3\left(\frac{14600}{T}\right)^{0.93} - m$$

At the date when the earliest estimates were made, no actual measures of stellar diameters were available. But in December, 1920, measures made with the 20-foot Michelson stellar interferometer, mounted on the 100-inch Hooker telescope at Mount Wilson, confirmed very closely the theoretical value for the angular diameter of α *Orionis*. Eddington had given 0.051 for the angular diameter of this star, the measured value of Michelson and Pease was 0.047 [¶] Subsequently the diameters of α *Bootis* and α *Scorpii* were measured and found to be 0.022 and 0.040, Eddington's estimate for them being 0.020, 0.043 respectively. With the best available values for the parallaxes of the three stars, α *Bootis*, α *Orionis*, and α *Scorpii*, their diameters have the respective values 34,000,000 km., 344,000,000 km., and 640,000,000 km respectively, as compared with 1,390,000 km for the sun [**] The last-named star, Antares, if placed at the sun's centre, would extend not only beyond the earth's orbit but well beyond the orbit of Mars

* *Potsdam Pub* xxiv No 76 1920

† *British Association Report* 1920, 42

‡ *Popular Astronomy* xxix 31, 1921

§ *Veroff d Universitätssternwarte zu Berlin-Babelsberg,* iii No 4, 1923

|| *Annalen van de Sterrewacht te Leiden* xiv 20, 1922

¶ *Ap J*, liii 249 1921

** Hale, The New Heavens 57, 1922

The existence of giant stars, much more luminous than the sun, was thus confirmed by direct measurement some fifteen years after Hertzsprung had first divided stars into two groups of high and low luminosity   The mean density of Antares is probably of the order of $10^{-8}\times$ the mean density of the sun, an unexpectedly low figure in view of its banded spectrum and of the slight ionization shown by the other lines in its spectrum   An indication that the diameter of *a Orionis* is varying along with its brightness and its radial velocity * suggests that there may be important applications of the stellar interferometer to be made to add to the understanding of the theory of stellar variation

39 Stellar Masses —The study of radiation has led to conclusions, verified by other investigations, on stellar temperatures and diameters   It remains to note how radiation enters into the question of stellar masses Eddington, in a series of papers,† has discussed the part that the pressure of radiation plays in the equilibrium of a star

With certain assumptions as to the high stage of ionization found in the interior of a star he found a simple relation connecting the mass, the absolute magnitude of a star and the coefficient of reduction of the constant of gravitation, β (when radiative pressure is taken into account in the pressure equation we replace G, the constant of gravitation, by βG)

The first striking result obtained by Eddington was that, within a small range of values for stellar masses (the range including the sun's mass), radiation pressure increased with increasing mass from a small fraction of gravitation to four-fifths of gravitation , at the same time the absolute magnitude brightened from that of extremely faint stars to that of the brightest known stars   When radiation

* *Pub A S P* xxxiv 346, 1922
† *M N R A S* lxxvii 16 596 1917 , lxxxiii 32, 98, 1922 *Ap J* , xlviii 205, 1918

pressure approaches gravitation in value the equilibrium of a star is much more liable to break down through such causes of instability as rotation, and thus stars many times the sun's mass would be likely to break up into smaller masses * On the other hand, stars much less massive than the sun would not be bright enough to be seen   Radiation pressure thus supplied a good reason why the visible stars should lie within a narrow range in mass, a state of affairs recognised from data as to binary stars, but first explained in terms of radiation   An extract from Eddington's table † gives his estimate for a star in radiative equilibrium of effective temperature 5200° K   (The absolute magnitude requires a small additional term $- 2 \log_{10} (T_e/5200)$ for stars of effective temperature $T_e°$)

TABLE IV

MASS AND ABSOLUTE MAGNITUDE

Mass ($\odot = 1$)	Absolute Magnitude	$1 - \beta$
0 1284	+ 14 143	0 001
0 2233	+ 11 513	0 003
0 4135	+ 8 615	0 010
1 004	+ 4 645	00 5
2 050	+ 1 884	0 14
3 774	— 0 052	0 26
7 117	— 1 718	0 40
19 62	— 3 919	0 60
37 67	— 5 162	0 70
90 63	— 6 714	0 80

Comparing the theoretical curve connecting mass and absolute magnitude with known values for individual stars,

* The most massive star so far discovered is v *Sagitarii*, a binary whose components together are more than 300 times the mass of the sun (Ludendorff *Sitz Preuss Akad d Wiss*, 1924, p 67)

† *M.N R A.S*, lxxxiv 310, 1924

Eddington found remarkably close agreement of observation and theory not only for the very luminous massive stars, but also for the fainter stars of small mass These latter stars had not previously been suspected of obeying the gas laws   the explanation offered by Eddington is that the high state of ionization holding within a star and the consequent stripping of atomic nuclei of their outer rings of electrons mean that it is still possible for the gas-laws to be obeyed, even for the high densities which prevail in the faint stars of small mass Another unexpected result of Eddington's investigation, in addition to the explanation of the narrow range of stellar masses and the obedience of dense stars to the gas-laws, is the high value given for the opacity of stars The stars are amazingly opaque to radiation The value for the opacity given by Eddington * for Capella is 150 in C G S units, the opacity is nearly constant throughout the star, and if we measured it at that layer of Capella where the density is that of the terrestrial atmosphere, we should get the surprising result that four-fifths of the radiation was absorbed in passing through a layer 15 cm thick

* *Nature*, cxi , supplement to 12th May, 1923, p x

MOTION IN THE LINE OF SIGHT

40 Doppler's Principle —Doppler * was the first to per
ceive that the wave theory of light involved a change in
the observed wave-length of light from a given source
corresponding to motion of the source relative to the ob
server   The application that he made of this idea to explai
the colour of stars was false in that the light from a sta
extends on both sides of the visible range of the spectrum
and changes due to the motion of a star in the line of sigh
would take place simultaneously at both ends of the spectrum
The slight shift in the position of maximum intensity woul
lead to no appreciable colour change for ordinary stella
velocities   It was Fizeau who, in 1848, lecturing to th
Societe Philomathique de Paris, pointed out that Doppler
principle could be applied to the position of a line in th
spectrum, and that the motion of a source relative to th
observer could be measured by the displacement of a spectr
line from its normal position

Let $c =$ the velocity of light, the same in all direction
$$(2\ 9982 \times 10^{10} \text{ cm /sec } in\ vacuo)\ \dagger$$
$n, \lambda =$ the frequency and wave length of a light vibr
tion emitted by a moving source and assum
to be independent of the motion of the sourc
$n', \lambda' =$ the observed frequency and wave-length of t
vibration

* *Abh d K Bohmischen Gesell d Wiss* , ii 467, 1842
† *Ap J* , lx 256, 1924

$u =$ the relative velocity of the source and the observer resolved along the line of sight and measured positively when the source recedes from the observer

Then consideration of the number of waves that reach the observer in a given time shows that

$$\frac{n}{n} = \frac{c - u}{c}$$

If $\delta\lambda =$ the displacement of the line in the spectrum towards the red, we have, for the case where u is small compared with c,

$$\frac{\delta\lambda}{\lambda} = \frac{\lambda' - \lambda}{\lambda} = \frac{n - n'}{n'},$$

since by definition

$$n'\lambda' = n\lambda = \frac{u}{c}$$

For a source receding at velocity u from the observer, we have an increase in the observed wave-length of $u\lambda/c$ for a line of undisplaced wave-length λ It has been a common practice to speak of $c\delta\lambda/\lambda$ as the velocity in the line of sight or the radial velocity of a star , this is taken to be positive when $\delta\lambda$ is positive, i e when the source is receding from the observer   For certain investigations, notably on novæ, the custom has been recently introduced of discussing certain displacements, varying directly with λ, in terms of a *displacement factor* $10^4 \delta\lambda/\lambda$, thus avoiding the issue as to whether the displacements are, or are not, due to velocity in the line of sight   (The velocity in km /sec is obtained from the displacement factor by multiplying the latter by 30)

41 Radial Velocity —Fizeau mentioned in his original paper how a study of line of sight velocities for the components of certain visual binaries would enable us to determine their parallaxes and, Mach, a few years later,* pointed

* *Sitzungsb d K Akad in Wien*, xli 543, 1860

out how the principle could be applied to distinguish between lines of solar and telluric origin in the solar spectrum   The general application to stellar velocities depends essentially on our correct identification of the lines of absorption or emission to be used in comparing the stellar spectrum with known terrestrial sources of light   There is no difficulty in this for stars, whose spectra are of well-determined types, and consistent results for different elements represented in the same stellar spectrum are now easily obtained   The early visual observations, with the exception of Keeler's * at the Lick Observatory, in 1890, proved unreliable   Vogel and Scheiner, at Potsdam, and Belopolsky, at Pulkovo, were amongst the pioneers in photographic determinations, their work dating from about 1890   It was at the Lick Observatory again, that greatly increased accuracy in the determinations of radial velocities by photographic methods was obtained in the hands of Professor Campbell   Working with the 36-inch telescope and the Mills spectrograph, he reduced the probable errors of radial velocities to one-fifth of their previous value and greatly diminished the prevalent systematic errors   His probable error was given at 0 5 to 0 25 km /sec , and this accuracy led at once to an enormous increase in the number of known spectroscopic binaries   At the present time the claim of the Lick Observatory to lead in all radial velocity work is being challenged by the Dominion Astrophysical Observatory at Victoria B C (where J S Plaskett, with the aid of a 72-inch reflector, is rapidly adding to our knowledge of the radial velocities of stars) and also by the Mount Wilson Observatory, where Adams has been carrying out a heavy programme of work with the 60-inch reflector

42. Applications to the Planets —The applications of the Doppler effect within the solar system are interesting

* *Pub Lick Obs* iii 195, 1894

PLATE 22
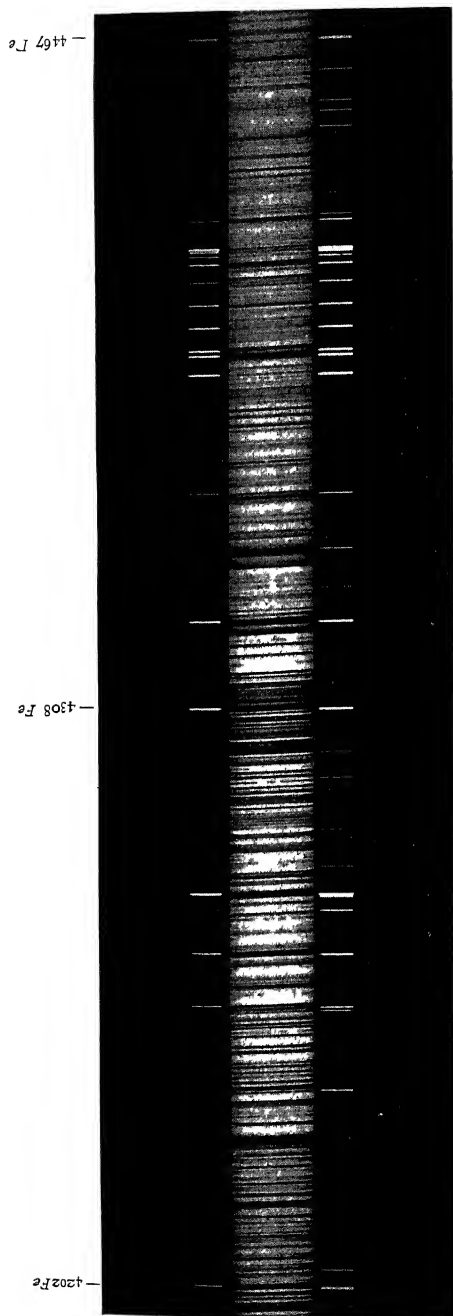
SPECTRUM OF JUPITER

Photographed by V M Slipher at the Lowell Observatory   Slant of lines measure   rate of rotation of planet   Comparison spectrum Fe and V

First, we may mention Keeler's observation of the rings of Saturn,* whereby he verified Clark Maxwell's theory of the nature of the rings   He placed the slit across the planet in the plane of the ring , the lines in the spectrogram corresponding to the ball came out inclined to the lines of the comparison spectrum, the natural result of the rotation of the planet , but the lines corresponding to the ansae of the rings had an opposite slope (Plate 20) to that of the lines due to the ball   This naturally follows from the fact that as you pass out along a radius of the planet's equator, the velocity in the line of sight due to the rotation steadily increases, but as you pass out along the plane of the ring, the velocity due to the orbital motion of the particles forming the ring decreases again   The known velocity of rotation of the principal planets with constant or nearly constant markings act as a check on the velocities found from the slope of the spectral lines and encourage confidence in the method when applied to planets of indefinite markings (Plate 22)   V M Slipher,† at the Lowell Observatory, has, in this way, determined the period of rotation of Uranus as being 10 h 50 m , the direction being retrograde or in the same sense as that of the revolution of its satellites   The period of rotation of Venus is still uncertain

43 Solar Rotation —As mentioned already, Mach saw the value of Doppler's principle as a means of sorting out, in the solar spectrum, lines of true solar origin (which would show relative shifts when photographed from the west and east limbs) from lines of telluric origin arising from absorption in our atmosphere   A measure of the shift in different solar latitudes leads, of course, to a determination of the sun's rotation   In this way the law of rotation was extended to the polar regions from the lower latitudes, to which previous determinations, obtained from the observed

* *Ap J* , 1 416, 1895   † *Lowell Obs Bull* No 53, 1912

motions of sunspots, had been limited   The newer deter-
minations are unaffected by variations in the drifts of the
spots, but they are, of course, affected by local currents and
by some uncertainty as to the depths of the layers involved
in producing the lines whose shifts are being measured *
As Adams showed,† the rotational velocity of gases at
the higher level corresponding to the hydrogen line Hα is
larger than for the lower level of the reversing layer   Also
the equatorial acceleration found for sunspots and the
reversing layer vanishes for the upper layers   The meaning
and results of these differences have not yet been worked
out in terms of the general problem of the circulation of the
solar atmosphere   Other questions remaining unsolved in
regard to the solar rotation are the variability of the rate
of rotation apart from temporary and local fluctuations and
also differences of behaviour between the northern and
southern hemispheres of the sun

44. Reduction to Sun —Before returning to the applica
tion of Doppler's principle to stellar investigations, it is as
well to give a brief account of the corrections that have to
be made to the observed radial velocity to allow for the
motion of the observer   We have to take into account (*a*)
the motion of the earth round the sun , (*b*) the motion of
the observer about the earth's axis , and (*c*) the motion of
the earth round the centre of inertia of the earth-moon
system   There is a further term allowing for the motion
of the sun round the centre of inertia of the solar system
This amounts at most to 0 015 km /sec , of which about
four-fifths comes from the Jupiter term   It can, in general,
be ignored   The values of the corrections (*a*), (*b*), and (*c*)
are given below ‡   The corrections are given with the
right sign for *addition* to the observed radial velocity of the

* See § 26 above   † *Ap J* , xxvii 217, 1908
‡ I follow the treatment of Schlesinger *Ap J* , ix 159   x 1,
1899

star, radial velocity being reckoned positive when away from the observer

(*a*) Correction for annual orbital motion—

Let λ, β = longitude and latitude of the observed star (taken in practice to the nearest minute)

O = sun's longitude at the time of observation (mid-exposure)

Π = longitude of sun at perigee
$= 281° 39' + 1 03' (t' - 1925 0)$, where t' is the date of the observation

a = semi-major axis of earth's orbit (149,600,000 km)

e = eccentricity of earth's orbit (0 0168)

T = length of sidereal year in seconds (31,558, 150)

v = mean velocity of earth in its orbit

$$= \frac{2\pi a}{T(1 - e^2)^{\frac{1}{2}}} = 29 77 \text{ km /sec}$$

Then the correction to the observed velocity of recession is

$$V_a = v \cos \beta \{\sin (O - \lambda) + e \sin (\Pi - \lambda)\}$$

We put $b = v \cos \beta$

$$c = v \cos \beta \ e \sin (\Pi - \lambda) ,$$

b and c can be determined once for all for a given body and are independent of the epoch—save for small secular corrections

Then $V_a = b \sin (O - \lambda) + c$

(*b*) Correction for daily motion—

Let A = earth's equatorial semi-diameter

τ = length of sidereal day in mean seconds (86164 1)

ϕ = latitude of observer

ρ = radius vector from earth's centre to observer

δ = declination of star

t = western hour angle of star

then $V_b = -\dfrac{2\pi A}{\tau} \rho \cos \phi \sin t \cos \delta$

For a particular observatory a table can be formed with t and δ as arguments   In general, t is taken as the time of mid-exposure of the plate   The maximum value of this correction at the equator is 0 47 km /sec

(c) For the monthly term we have a similar expression to that for the annual term, but we can neglect the eccentricity of the lunar orbit and its inclination to the ecliptic

Let $\mathbb{C} =$ longitude of moon at time of observation

Then $V_c = v_m \cos \beta \sin (\mathbb{C} - \lambda)$,

where $v_m = 0\ 0124$ km /sec , taking the mean distance of the moon as 60 27A, and the mass of the earth as 81 70 times the moon's mass

The total correction to the observed velocity of the star to allow for the observer's velocity in the line of sight relative to the sun is $V_a + V_b + V_c$ For refined work it may be necessary to take into account the velocity of the sun relative to the centre of inertia of the solar system

45 The Solar Motion —Herschel, in 1783, first investigated [*] the motion of the solar system among the stars from the study of the thirteen proper motions of stars then known He found that the sun was apparently moving towards λ *Herculis*   Since then many statistical studies of the sun's motion have been made   Kapteyn showed [†] that the hypothesis of random motion for the stars on which these determinations were mainly based was not well founded, and that the main body of the stars showed preferential motions in two directions   The two star-drifts can be represented as a passage of one group of stars through another, the solar motion being superimposed on them From a study of the proper motions in Lewis Boss's '' Preliminary General Catalogue,'' Eddington [‡] derived a position

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[*] *Phil Trans*, lxxiii 247, 1783
[†] *British Association Report* 1905 257
[‡] See   Stellar Movements   Eddington p 102, 1914

for the apex towards which the sun is moving as

$$\alpha = 267\,3°, \qquad \delta = +\,36\,4°$$

Campbell's position * of the solar apex and value for the sun's velocity derived from the radial velocities of 1047 stars was

$$\alpha = 273\,5°, \qquad \delta = +\,28\,0°, \qquad \text{and } V = 17\,73 \text{ km /sec}$$

This gives a further correction to the observed velocity of a star at a position (α, δ) as

$$V_s = +\,17\,73 \cos(\alpha - 273°) \cos(\delta - 28°) \text{ km /sec}$$

The figures must remain for the present uncertain   There are several outstanding puzzles in connection with stellar velocities in general and the radial velocities fully share in these puzzles   There is evidence for the presence of at least two other groups of stars systematically drifting through space, in addition to the two principal streams discovered by Kapteyn   It is inevitable that the position of the solar apex should depend on the stars selected for use in its determination   This comes out, if we determine the solar motion from stars of different spectral types,† or from stars of different velocities in space   Thus Strömberg ‡ has shown that the solar velocity V, comes out at 20 6 km /sec when determined from 1026 stars of types F to M of space-velocities lying between 0 and 60 km /sec , but from a study of 210 stars of the same spectral types with space velocities between 60 and 100 km /sec , he has found that the solar velocity, V, comes out at 36 3 km /sec   And further, the value for the solar velocity increases rapidly as the velocities of the stars used to determine it also increase   This must mean that the fast-moving stars are streaming

*   Stellar Motions   Campbell, p 189, 1913

† Boss, _A J_ , xxvi 187 1911

‡ Stromberg, _Ap J_ lvi 265 1922

systematically in a direction opposed to the sun's motion,
Oort * gives the apex for these fast stars at $\alpha=125°$, $\delta=-44°$

46 Stellar Motions and Spectral Types —Applying the
correction for the sun's motion to the observed velocity of
a star, we get the radial velocity of the star relative to the
system of stars employed in the determination of the solar
motion A statistical study of a large number of stellar
velocities brings us at once face to face with a number of
problems Thus we find that stars of early type, B0 to B9,
show a marked excess of positive radial velocities over
negative velocities The mean value for 138 of these stars was
found by Campbell to be $+ 4 93$ km /sec † It is improbable
that the universe of B stars is expanding at this rate, and
some other explanation of the mean positive radial velocity
seems to be required It has been partly traced to errors
in the assumed laboratory wave-lengths of the stellar lines
used in determining the radial velocities,‡ but the complete
explanation can hardly come in this way For Gerasimovič
has shown § that this outstanding mean velocity term, the
so-called K-term, varies in value with the star's mass,
while Freundlich and v d Pahlen have shown ‖ that it
varies with the galactic longitude of the stars The K-term
appears to consist of a constant part, which may be due to
a downward convection current in high-level gases of the
stellar atmospheres,¶ and of a variable part which is prob-
ably connected with the phenomena of star-streaming A
general outward streaming in the directions of the vertex
(Galactic longitude 347° and latitude 0°), and in the opposite
direction seems to exist alongside a general inward streaming

* *B A N* No 23 1922
† " Stellar Motions p 202
‡ Albrecht, *Ap J*, lv 361, 1922 and lvii 57, 1923
§ *A N*, ccxxi 163, 1924
‖ *Ibid*, ccxviii 369 1923
¶ Campbell *Lick Obs Bull*, viii 71 1914 St John *Ap J*
lx. 48, 1924

ın Galactıc longıtudes 131°, 311° The explanatıon of these motıons, ıf they should be confirmed later, ıs yet to be found

Further questions are raısed by the dıstrıbutıon of radıal velocıtıes among the dıfferent spectral types The followıng table, gıven by Plaskett,* shows thıs plaınly —

TABLE V

Spectral Class and Radial Velocity

Spectral Class	Resıdual Radıal Velocıty
B	6 5 km /sec
A	10 9
F	14 4
G	15 0
K	16 8
M	17 1
N	18 0
R	21
Se	24
Me	35
O	25 5
P	30 0

That there ıs a relatıonshıp between a star's spectral type and ıts velocıty ın space ıs clear Both, however, depend upon a thırd factor, namely, the mass of the star

Halm † has shown that the correlatıon between stellar mass and velocıty ıs a close approxımatıon to that requıred by Maxwell's law of equıpartıtıon of energy, which enuncıates that the kınetıc energy of a system shall be evenly dıvıded between the more massıve and less massıve members of the system, the more massıve members movıng more slowly Our galactıc system ın the course of ıts evolutıon

has moved part way at least to a steady state in which the distribution of velocities obey Maxwell's law * This would seem to be one fundamental point The relation which we saw in the preceding chapter to hold between a star's mass and its absolute brightness and spectral type, when in radiative equilibrium, provides another The observed connection between a star's spectrum and its radial velocity is a relation resulting from the dependence of these two properties of the star on its mass

47 Spectroscopic Binaries —It was in 1889 that E C Pickering announced that the doubling of the [K] line, and certain other lines in the spectrum of ζ *Ursae Majoris* (Mizar) indicated that it was a binary star with a period of 104 days † Vogel quickly followed this announcement with a statement that the variable β *Persei* (Algol) showed a spectrum which gave a varying velocity Further, the changes in velocity agreed with what would have been expected on Goodricke's hypothesis ‡ that *Algol* was an eclipsing binary, and that the spectrum belonged to the bright companion Since then many hundreds of spectroscopic binaries have been discovered—for the most part at the great American and Canadian observatories

48. Orbits of Spectroscopic Binaries —The radial velocity of one member of a binary when plotted against the time, gives a periodic curve from which we can find the elements of the orbit (assumed elliptic) of the star relative to the centre of inertia of the binary system In the determination of orbits for spectroscopic binaries the Canadian and American astronomers again have most results to show It will

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* The class O stars and the planetary nebulæ, being very massive and having high velocities, provide important exceptions to this Maxwellian distribution

† *M N.R A S*, 1 296, 1890

‡ *Phil Trans*, lxxiii. 482, 1783

only be possible here to give a brief description of the methods involved *

Take as axis of z the line from the observer to the star measuring z positive away from the observer   Take the xy plane tangential to the celestial sphere through the origin of co-ordinates, the centre of inertia of the binary system

Let $\imath =$ the inclination of the orbit plane to the xy plane taken between 0° and 90°

$\omega =$ the longitude of periastron from the ascending node of the orbit on the xy plane, i e from the node at which the star is moving away from the observer

$\theta =$ the longitude of the star from the ascending node

$v =$ the true anomaly of the star,

so that $v = \theta - \omega$

$a =$ the semi-major axis of the star's orbit round the centre of mass of the system, expressed in kilometres

$e =$ the eccentricity of the orbit

$p = a(1 - e^2)$

$r =$ the radius vector from origin to star, expressed in kilometres

$m, m' =$ the masses of the star and of its companion

Then $z = r \sin \imath \sin \theta$

so that $\dfrac{dz}{dt} = \sin \imath \sin \theta \, \dfrac{dr}{dt} + r \sin \imath \cos \theta \, \dfrac{d\theta}{dt}$

But if $f = km'^{\frac{3}{2}}/(m + m')$ where k is the Gaussian constant,

then $\dfrac{dr}{dt} = \dfrac{f}{\sqrt{p}} e \sin (\theta - \omega),$

$r \dfrac{d\theta}{dt} = \dfrac{f\sqrt{p}}{r} = \dfrac{f}{\sqrt{p}} \Big\{ 1 + e \cos (\theta - \omega) \Big\}$

* For a very complete account see ' The Binary Stars," by R G Aitken (1918), Ch VI   Lists of orbits which have been determined can be found in the annual reports of the Council of the R A S   The notation adopted is that recommended by the International Astronomical Union, *Trans I A U* , 1 22 and 170 1922

so that $\dfrac{dz}{dt} = \dfrac{f}{\sqrt{p}} \sin \imath [e \sin \theta \sin (\theta - \omega)$

$$+ \cos \theta \{ \mathrm{I} + e \cos (\theta - \omega) \}]$$

$$= \dfrac{f}{\sqrt{p}} \sin \imath (\cos \theta + e \cos \omega)$$

$\dfrac{dz}{dt}$ is the observed velocity in the line of sight less the velocity γ of the centre of inertia of the system in the line of sight

Put $D = \dfrac{f}{\sqrt{p}} \sin \imath$ and $C = \gamma + De \cos \omega$,

then the observed radial velocity $\dfrac{dz'}{dt} = C + D \cos \theta$

Plot $\dfrac{dz'}{dt}$ against the abscissa t, a study of the measured velocities leads by a method of trial and error to a determination of the period, P, of the binary When this has been determined as accurately as possible, all the observed values of $\dfrac{dz'}{dt}$ are plotted against their phase in the assumed period, and a smooth curve is drawn through the plotted points

The curve has a maximum M_1 and a minimum M_2

$$M_1 = C + D$$
$$M_2 = C - D$$

from which we have $C = (M_1 + M_2)/2$, $D = (M_1 - M_2)/2$ Draw on the graph a line parallel to the axis of abscissæ at a distance C above it, and measure a new ordinate Z from this line

We have $\qquad \dfrac{dZ}{dt} = \zeta = D \cos \theta$

Now trace the curve on to tracing paper and invert it on the line C, move it forward half a period and find the intersections of the two curves (One curve has to be repeated for an extra half period) Of the 4 points of intersection, choose the two which lie on different branches of

the curve and are separated in the orbit by half the period
Then we have $\zeta_1/D = \cos\theta_1$, $\zeta_2/D = \cos\theta_2 = -\cos\theta_1$, since
by the construction $\zeta_2 = -\zeta_1$ Also $\theta_2 = \theta_1, + \pi$ for the pair
of points selected

But $$\theta_1 = v_1 + \omega,\ \theta_2 = v_2 + \omega,$$
$$v_2 = v_1 + \pi,$$

and these two points must correspond to periastron and
apastron, the only points for which v increases by π in a
half period The steeper slope of the curve belongs to
periastron, for which $v = 0$ and $\theta = \omega$ or $\zeta/D = \cos\omega$
This point determines the value of ω

Next to determine the eccentricity of the orbit take two
points at epochs t, t' (not exactly half a period apart) such
that
$$\zeta = -\zeta'$$
or $$\cos\theta = -\cos\theta'$$
i e $$\theta' = \theta + \pi \text{ and } v' = v + \pi$$

If $w =$ the eccentric anomaly of the star corresponding
true anomaly v

P $=$ the period

and $T_0 =$ the epoch at periastron,

we have $$w - e\sin w = 2\pi\,(t - T_0)/P$$
$$w' - e\sin w' = 2\pi\,(t' - T_0)/P$$
$$w - w' - e\,(\sin w - \sin w') = 2\pi\,(t - t')/P$$

But $$\tan\frac{v}{2} = \left(\frac{1+e}{1-e}\right)^{\frac{1}{2}}\tan\frac{w}{2}, \qquad \tan\frac{v'}{2} = \left(\frac{1+e}{1-e}\right)^{\frac{1}{2}}\tan\frac{w'}{2}$$

and since $$v' - v = \pi, \qquad \tan\frac{v'}{2}\ \tan\frac{v}{2} = -1$$

$$\tan\frac{w}{2}\ \tan\frac{w'}{2} = \frac{e-1}{e+1}$$

$$e = \cos\frac{w'-w}{2} \Big/ \cos\frac{w'+w}{2}$$

and $\qquad e(\sin w' - \sin w) = \sin(w' - w)$

i e substituting above

$$w' - w - \sin(w' - w) = 2\pi(t' - t)/\mathrm{P}$$

Put $\quad \dfrac{w' - w}{2} = \eta, \dfrac{w' + w}{2} = \xi$, so that $e = \cos\eta/\cos\xi$

Then $\qquad 2\eta - \sin 2\eta = 2\pi(t' - t)/\mathrm{P}$

Schwarzschild published * a table giving η in terms of $(t' - t)/\mathrm{P}$, also since $\cos(v + \omega) = \cos\theta = \zeta/\mathrm{D}$

η and v are both known from the selected points in the figure

But $\qquad \tan\dfrac{w}{2}\Big/\tan\dfrac{w'}{2} = \tan\dfrac{v}{2}\Big/\tan\dfrac{v'}{2} = -\tan^2\dfrac{v}{2}$

or $\qquad \sin\dfrac{w}{2}\cos\dfrac{w'}{2}\Big/\cos\dfrac{w}{2}\sin\dfrac{w'}{2} = \left(-\sin^2\dfrac{v}{2}\right)\Big/\cos^2\dfrac{v}{2}$

i e $\qquad\qquad \sin\dfrac{w' + w}{2} = \cos v \sin\dfrac{w' - w}{2}$

or $\qquad\qquad\qquad \sin\xi = \cos v \sin\eta$

ξ is determined, i e $e = \cos\eta/\cos\xi$ is known

We cannot fully determine the orbit, the inclination and size of the major axis not being given independently in the spectroscopic orbit

We have $\mathrm{D} = \dfrac{f\sin\imath}{p^{\frac{1}{2}}} = \dfrac{f\sin\imath}{a^{\frac{1}{2}}(\mathrm{I} - e^2)^{\frac{1}{4}}}$

and the mean motion $= 2\pi/\mathrm{P} = f/a^{\frac{3}{2}}$

whence we determine

$$a\sin\imath = \mathrm{D}\dfrac{\mathrm{P}}{2\pi}(\mathrm{I} - e^2)^{\frac{1}{2}}$$

For the masses, again dependent on $\imath$, we have

$$\dfrac{m^3\sin^3\imath}{(m + m')^2} = \dfrac{\mathrm{P}}{2\pi k^2}\mathrm{D}^3(\mathrm{I} - e^2)^{\frac{3}{2}}$$

* *A N* clu 65, 1900

If we measure m, m' in terms of the sun's mass, P in days and D in terms of km /sec the coefficient $\frac{1}{2\pi k^2}$, comes out as $1\ 03 \times 10^{-7}$, so that the equation for the masses becomes

$$\frac{m^3 \sin^3 i}{(m + m')^2} = 1\ 03 \times 10^{-7}\ PD^3(1 - e^2)^{\frac{3}{2}}$$

The above work and formulæ all apply to the motion of one star round the centre of inertia of the system   They have to be modified slightly if the motions of the two stars relative to each other are given by the spectroscopic observations *

49 Spectroscopic and Visual Binaries —Binary stars fall at present into two well-defined classes, the spectroscopic binaries and the visual binaries   Observational difficulties on both sides have so far prevented the gap from being filled   Michelson's stellar interferometer may have one application in filling this gap †   There are certain characteristics of the orbits of the two classes, resemblances and differences, which should be noted   The visual binaries have long periods and large eccentricities, the spectroscopic binaries have short periods and small eccentricities   The gap between the two classes is best seen from their periods The spectroscopic periods range mostly from 0 142 d to less than 150 days, the visual from 5 7 years upwards   The characteristics of the two classes may be shown from Table VI given by Aitken (see p 98) ‡

Further, we must note that whereas the majority of spectroscopic binaries are of B or A type,§ the majority of

* For references to the methods of improving this preliminary orbit by the method of least squares see Aitken, " The Binary Stars, ' p 160

† See Merrill, *Ap J* , lvi 40 1922

‡ *Ibid*   p 196

§ See below, Chapter VIII, for definition of spectral types

7

TABLE VI

BINARY STAR CHARACTERISTICS

	Number	Average Period	Average Eccentricity
Sp Bin	46	2 75 days	0 047
,, ,,	19	7 80 ,,	0 147
,, ,,	25	23 00 ,,	0 324
,, ,,	29	555 ,,	0 350
Vis Bin	30	31 3 years	0 423
, ,,	20	74 4 ,,	0 514
, ,	18	170 ,	0 539

visual binaries are of G type , in fact, none of these latter
are of B type

Again, the periods of the binaries increase steadily on
the whole as the stars are classed in the order of the Harvard
spectral classifications B, A, F, G, K, M   The evidence is
not very clear save for the large number of B type stars of
short period and the large number of G type stars of long
period but, after allowing for the effect of certain observa-
tional difficulties, Aitken * sums up the evidence as, on the
whole, definitely in favour of an increase of the period with
advancing spectral class

A study of the masses of binaries gives further evidence
for a progressive change with spectral type   For spectro-
scopic binaries Aitken † gives the following table —

TABLE VII

MASSES OF BINARY STARS

Spectrum	m	m	m'/m
B —B8	12 3	8 5	0 69
B9—A5	3 0	2 4	0 80
F5—G	1 9	1 7	0 89

* " The Binary Stars, p 200   † *Ibid* , p 206

For visual binaries of known parallax, Miller and Pitman *
give the following table —

Spectrum	B	A	F	G	K	M
Average Mass	14 91	3 49	3 92	1 77	1 57	0 65

Probably the masses of the stellar components are the
decisive factors in producing the relationship between spec-
tral types and periods for binaries   Mass, absolute magni-
tude, and spectrum are closely related for stars as a whole,
the relationship being deduced mainly from details available
for components of binary stars   The secondary component
of a giant is of earlier type (i e nearer B than M) than the
primary †   on the other hand, for a dwarf star the secon-
dary component is generally of later type than the primary
In both cases the difference in spectral type between the
two components increases with the difference in their magni-
tudes   Components of visual binaries tend, on the whole,
to be equal in mass and similar in spectral class, the tendency
increasing with an increase in mass   This does not agree
with what is found in the case of the spectroscopic binaries,
where the mass ratio tends to differ more from unity as the
total mass increases   It is one of the distinctions between
the two classes of binaries pointing to some fundamental
differences in their history and evolution

50 Origin of Binaries —Various theories have been
advanced as to the formation of binary stars   Here we
shall consider merely the theory of formation by fission
from a parent body, originally a rotating nebula   The

* *A J*, xxxiv 131 1922

† Leonard, *Lick Obs Bull*, No 343, 1923 , Doig, *M N R A S*,
lxxxii 322, 1922

process of development has been sketched by Jeans * In
the process of contraction with consequent increased rota-
tion a stellar nucleus, formed in an arm of a parent nebula,
may first lose matter by ejection of jets from its own equator
A surrounding atmosphere may be formed at the expense
of the central mass, whose condensation continues A
spheroidal, then an ellipsoidal, shape is assumed by this
condensing nucleus which later becomes pear-shaped and
finally may break up into two detached masses It is very
difficult to see how this process of development can apply
to the giant binaries of low density, but it may well apply
to the dwarfs After fission tidal friction may well operate
to cause (1) increasing separation , (2) increasing period
and (3) increasing eccentricity † This is well in accord
with the facts discussed in the last paragraph so far a
dwarf binaries are concerned But we may not assume
that every individual binary passes through the whole range
of values given by the spectroscopic and visual binaries, i
the development is to be traced to forces originating inside
the binary system Dynamically such a course is impossible
To secure an explanation of the observed phenomena a
representing one chain of development, Jeans suggests that
the visual binaries of late spectral type date from an epoch
when stars were more closely packed than is now generall
the case Their development along the lines of increasin
separation and eccentricity is to be traced mainly to the effect
of encounters with other stellar systems The B-type spec
troscopic binaries were born at a later epoch and probabl
by some other process than that of the simple fission of
parent nucleus , by the time of their birth our galaxy ha
opened out and stellar encounters had become less frequen

* ' Problems of Cosmogony Jeans 1919 The reader is r
ferred to this book for the most complete mathematical treatmer
of the question as yet available

† See Table VI §49

These binaries could have changed but slightly in period and eccentricity since their birth, and are not likely to change much in the future   The evolution which has left its mark on binary systems of earlier date belongs to a distant past The present processes are slow and will not provide many changes of great importance   It is true that the components of the giant spectroscopic binaries may themselves break into two, providing triple and multiple systems Such systems are known both from visual and spectroscopic observations, and the types of systems known agree on the whole well with the requirements of the theory of fission * But, apart from this, marked changes in binary systems are unlikely, unless, in due course, our universe or portions of it pass once more through a stage where stars are more closely packed than at present   Smart has pointed out † that loss of mass accompanying radiation would allow *very massive* spectroscopic binaries to evolve into dwarf visual binaries, to that extent the general views of Jeans given above need modification

* Russell *Ap J*   xxxi 200, 1910
† *Observatory* xlviii 95, 1925

STELLAR CLASSIFICATION

51 Early Work—(*a*) *Secchi's Types* —Secchi was the first *
to form a simple framework into which to fit his observed
spectra He suggested four types as sufficient, and we may
note that his classification was empirical, being independent
of any theory of evolution His grouping was as follows —

Type I White or blue stars The presence of dark
hydrogen lines and the absence or the faint presence only
of metallic lines are to be noticed Typical stars are *a Canis
Majoris* and *a Lyræ*

Type II Yellow stars These stars have a great
number of fine dark lines in their spectra Typical stars
are the sun, *a Aurigæ*, and *a Boötis*

Type III Red and orange stars, including most of the
variable stars These stars have numerous dark bands or
flutings, sharp on the violet side and fading away towards
the red Typical stars are *a Orionis, o Ceti, a Scorpii
a Herculis*

Type IV Faint stars of a deep red colour, whose flutings
shade off in the opposite direction to those of Type III stars
Typical stars are 152 *Schjellerup*, 19 *Piscium*

Type V was suggested later by E C Pickering † to
include the bright-lined Wolf-Rayet stars and the planetary
nebulæ

(*b*) *Vogel's Classes* —The next important classification

* *C R* lxiii 621 1866   † *A N* cxxvii 1, 1891

was Vogel's,* based on a definite view of the orderly development of stars in time from one spectral stage to another The word " class " is used of Vogel's scheme, the word " type " applying to Secchi's work The chief difference from Secchi's scheme was in the subdivision of the classes and the re-numbering of Secchi's Types III and IV as Classes III (a) and III (b) respectively Vogel's view was that the difference between these two types was not generic enough to justify their being placed in separate classes Pickering's Type V was placed by Vogel in Class II (b)

Following the sequence now generally adopted, we may give Vogel's classification briefly as follows —

Class II (b) The bright-lined Wolf-Rayet stars (see below, Harvard Class O , Type V)

Class Ic1 Stars with bright hydrogen lines (but without the characteristic Wolf-Rayet bands)

Class Ic2 Stars as in the previous class, but with bright metallic enhanced lines also present

These two classes represent peculiar spectra that really lie outside the main schemes of classification

Class Ib The helium, or so-called " Orion " stars, with strong dark helium and hydrogen lines Absorption lines due to carbon, oxygen, and nitrogen are also present and strong A few enhanced lines of metals also present (Class B , Type I)

Class Ia1 Hydrogen lines present alone Probably not a true class

Class Ia2 Hydrogen present and the metallic lines much stronger and more frequent than in Class I, b Helium absent (Class A , Type I)

Class Ia3 The [K] line of calcium as strong as the hydrogen lines (Classes A5, F0, F5 , Type I)

Class II (a) The hydrogen lines lose their prominence

* *A N* lxxxiv 113 1874 *Ap J* , ii 333 1895

among the numerous metallic lines (Classes F8, G, K0, K2 , Type II)

Class III (a)   Yellowish-red and reddish stars with dark bands, sharp on the violet side and shading off towards the red (Classes K5, M, S , Type III)

Class III (b)   Stars of a deep red colour with carbon bands shading off towards the violet (Classes R, N Type IV)

(c) *Harvard Classes* —In the Draper Catalogue,* Pickering and his colleagues at Harvard developed a scheme, using the letters A, B   Q to denote different spectral classes   Miss Cannon † modified this scheme by adding to each class numbers 0, 1   9, to allow of grading of classes and intermediate stages   Thus F3G—or more shortly F3—indicates that a star is three-tenths of the way from a typical F or Fo star to a typical G or Go star   The behaviour of certain *bright* lines or bands was used by Miss Cannon in further subdividing the Harvard classes, the notation employed being of the type Md, Oa   In the latest Harvard Catalogue, the new Henry Draper Catalogue,‡ which gives the spectra of all stars down to the ninth magnitude the letters P, O, B A, F, G, K, M, N, R, S and Q alone survive in use   Details are given below in § 54

An entirely different scheme of classification was attempted also at Harvard by Miss Maury §   She divided the stars into twenty-two groups, which she subdivided again by the affixes *a, b, c*, according to the behaviour of certain *dark* lines in the spectrum   Recently it has been pointed out that her affix *c*, indicating the presence of unusually sharp lines, corresponds to a condition of low density, typical of the giant stars   Her sub-class *b* denoted spectra with unusually broad and diffuse lines, sub-class *c* spectra with unusually sharp lines, and sub-class *a* intermediate

* *Harvard Annals* xxvii 1890   † *Ibid* xxviii Part II 1901
‡ *Ibid* xci xcix 1918-24   § *Ibid* xxviii Part I, 1897

spectra   It may be useful to give here the connection between the two Harvard schemes, so that the frequent references to Miss Maury's scheme in astronomical literature can be readily referred to the Draper classification

TABLE VIII

HARVARD CLASSIFICATIONS

Maury s Group	Draper	Maury's Group	Draper	Maury's Group	Draper
I	Oe5	IX	A2	XVI	K5
II	Bo	X	A5	XVII and XVIII	Ma or Mo
III	B1	XI	Fo	XIX	Mb or M3
IV	B2	XII	F5	XX	Md or Me
V	B5	XIII	F8	XXI	N
VI	B8	XIV	Go	XXII	O (Wolf-Rayet)
VII and VIII	Ao	XV	Ko	———	

(d) Further schemes which must be mentioned are McClean's six divisions * and Sir Norman Lockyer's two schemes †   The latter provided alternatively six groups (I to VI), which he then subdivided, or more usually a scheme of 16 groups called after some typical star, e g Polarian, Algolian   The fundamental ideas of Lockyer's scheme—that the stars of a given spectral type must be divided into two classes according as they belong to the branch of ascending or descending temperature in the evolution scale—came later to be generally accepted, even though the actual details of his subdivisions have not been generally adopted

A comparison between the Draper Classes and the Lockyer groups shows a good deal of cross grouping,‡ and indicates the following as the best comparison table —

* *Phil Trans* cxci 127 1897
† *Ibid* clxxxiv 675 1892 and *Proc R S* , lxv 186, 1899
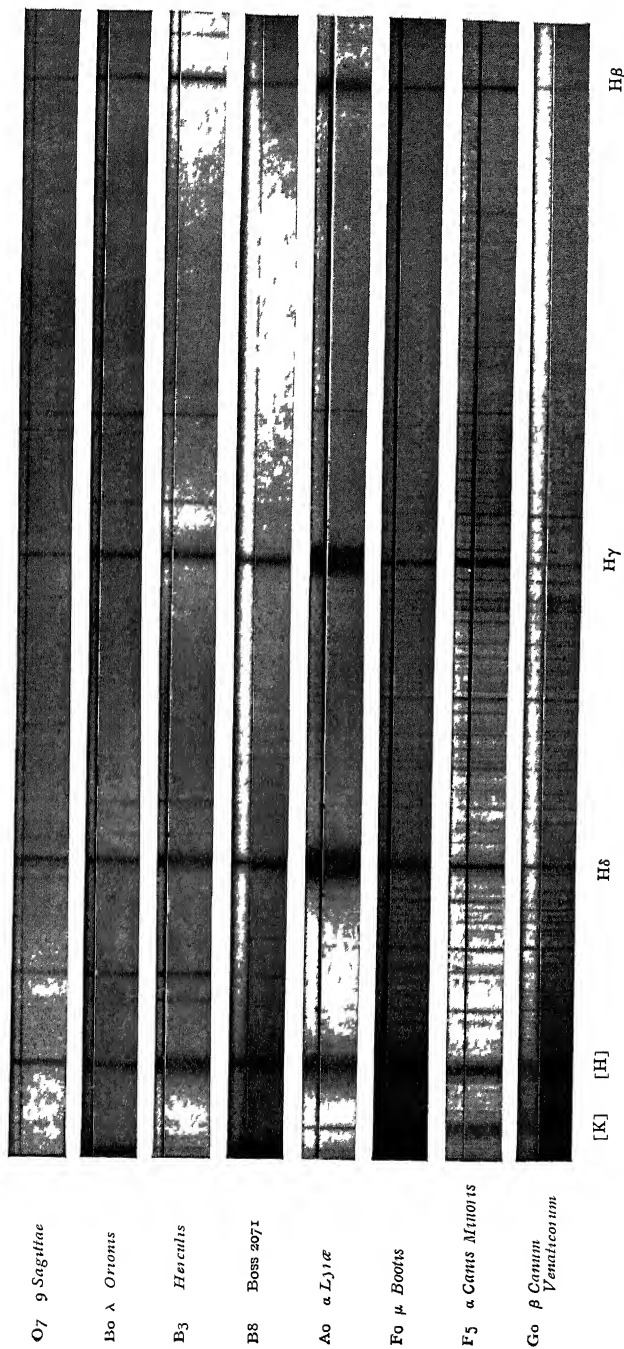‡ *Hill Obs Bull* , No IV 191

TABLE IX

LOCKYER'S SPECTRAL TYPES

Ascending Temperatures		Descending Temperatures	
Lockyer	Harvard	Lockyer	Harvird
Antarian	M	Piscian	N
Aldebarian	G, K	Arcturian	G K
Polarian	F2	Procyonian	F5
Cygnian	A2	Sirian	A
Rigelian	B9	Markabian	A
Taurian	B3	Algolian	B8
Crucian	B3-2	Achernian	B3
		Almitamian B2	
		Argonian O	

We may note that the extension of the spectrum made available for examination by the use of photography has not affected very much the main classification schemes worked out by the early visual observers, although it may have modified the placing of individual stars in different transition groups An idea of the chaotic condition of spectral classification in the earlier work may be given by the following list of designations for the star Procyon —

Secchi	Type I
Vogel	Class I(a) and later Ia3
Pickering	F
Miss Cannon	F5G or F5
Miss Maury	XII A
McClean	Division III
Lockyer	$\begin{cases} \text{A }(\beta)\text{ 3 or Group V} \\ \text{Procyonian} \end{cases}$

52 Nature of Classification Sequence —The above-mentioned schemes of classification depend on variations in the main features of the stellar spectra   It is remarkable in how small a number of different types we can include the

PLATE 23

O7   9 *Sagittae*

B0   λ *Orionis*

B3   *Herculis*

B8   *Boss 2071*

A0   α *Lyræ*

F0   μ *Bootis*

F5   α *Canis Minoris*

G0   β *Canum Venaticorum*

[K] [H]

Hδ   Hγ   Hβ

TYPICAL STELLAR SPECTRA—EARLY TYPES

In each case the untouched stellar spectrum is placed immediately above the artifically widened spectrum so that false lines in the latter may be recognised as such
The spectrograms were obtained with the 72 inch reflector of the Dominion Astrophysical Observatory Victoria B C

PLATE 24

G₁   ι *Persei*

K₀   γ *Andromedæ*

K₅   α *Hydræ*

M₁   α *Orionis*

M₇   R *Lyræ*

M₈ 40 *Coronæ*
       Borealis

M₉   o *Ceti*

Hδ   Hγ   Hβ
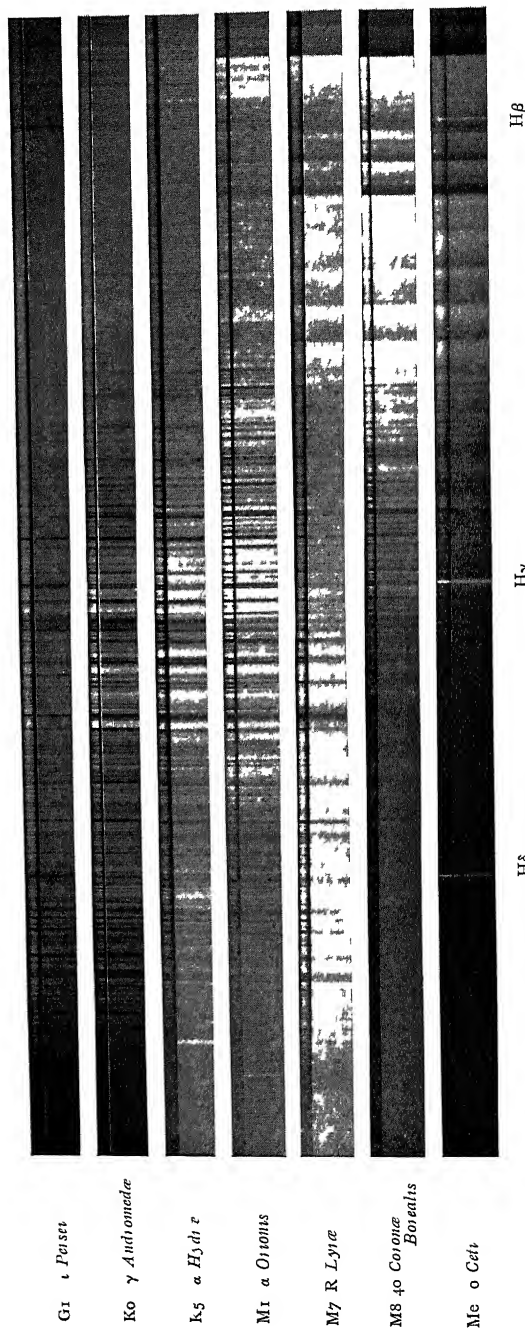
TYPICAL STELLAR SPECTRA—LATE TYPES

In each case the untouched stellar spectrum is placed immediately above the artificially widened spectrum so that false lines in the latter may be recognized as such
The spectrograms were obtained with the 72-inch reflector of the Dominion Astrophysical Observatory Victoria B C

great majority of the stars   Over 99 per cent of the stars fall into one or other of the Harvard classes B, A, F, G, K and M   And it is noteworthy that inside these types the stars form a *linear* sequence   Only one physical condition has to be looked for whose variation from star to star is accompanied by changes in the stellar spectra   Differences of temperature are generally accepted as providing the chief reason for differences in spectra   We are not here concerned with underlying factors that govern the temperature nor with the manner in which the temperature governs the resulting spectrum   Our interest here lies mainly with the spectral sequence itself O-B-A-F-G-K-M (with the alternative endings G-S or G-R-N), which runs in the order of descending temperatures (Plates 23, 24)   We have, at first the Balmer series of hydrogen and lines due to ionized helium, the spectra frequently containing some bright lines   The bright lines vanish and fresh, strong dark lines, due to ionized nitrogen, silicon, carbon, and oxygen develop, apparently in that order—the true order may be fixed when we have full knowledge of the series relationships of the lines concerned and the ionization potentials * of the elements   These lines weaken and we get lines due to non-ionized helium strengthening along with lines due to magnesium, iron, calcium, titanium, strontium, etc   Most of these lines come from ionized atoms of the elements   Helium vanishes and arc lines of the metals strengthen at the expense of the spark lines, i e lines due to the neutral atom replace those due to the ionized atom   Fresh elements make their appearance and finally, along one of two or three main lines, we find bands of compounds appearing in the spectra

    We give briefly the classes of the Draper Catalogue, as

* The ionization potential is the number of volts through which an electron must fall in order to acquire the energy necessary to ionize a single molecule of the gas

defined in the sequence of these chemical changes In
Class O5 we find the *He* II lines at their strongest, and we
get evidence of *N* III at 4634, 4642 In Class O7 N III 4097
is at its strongest, and *Si* IV 4089 is well present, as also
C III 4647 *He* I is stronger than *He* II In Class O9 we
get *O* III 3962 at its strongest, *Si* IV 4089 very strong, and
Mg II 4481 well present In Class Bo the *He* I lines and the
Si III lines at 4552 6, 4567 8, 4574 7 are becoming fairly
strong The *Si* IV and the *C* III lines are at maximum
strength, and we get the first traces of the line [K], *Ca* II
3933 7 In Class B1 the *Si* III lines at 4552 6, 4567 8,
4574 7 and the *He* I lines are stronger than the *Si* IV and
C III lines so prominent in Class O9, the *Si* III lines reaching
maximum strength in Classes B1, B2 By this time the
line at 4650 is mainly due to *O* II 4649 1 , *O* II is at its
strongest about this stage In Class B2, the *He* I lines are
at maximum, being next in strength to the hydrogen lines
which are paramount throughout the B class In Class B5
a new set of lines begin to be prominent, of which we may
mention *Si* II 4128, 4131, and *Mg* II 4481 2, as well as
Ca II 3933 7 These and other enhanced lines strengthen
in Class B8, the *Si* II lines 4128, 4131 being at their strongest ,
most of the *He* I lines are also still strong At this stage
He I drops rapidly out, showing a few lines in Class B9 and
being practically gone in Class Ao At this stage the
spectrum is mainly hydrogen and enhanced metallic lines,
but the stronger arc lines begin to appear, and in Class A2
we find the line *Ca* I 4227 The chief changes now are the
growing importance of arc lines of metals relative to the
spark lines and to hydrogen , by the time we come to
Class F5 we find the arc lines of iron and titanium about
of equal strength with the enhanced spark lines, the [g]
line, *Ca* I 4227, very well marked and the hydrocarbon
band [G] just beginning As we pass along the sequence
other elements such as vanadium begin to appear, this

element being strongly represented in Class K5 The titanium oxide bands also begin to appear at this point, the main sequence leading to Class M Meanwhile, at an earlier stage G5, carbon bands had begun to appear in a few stars leading in a steady sequence to Classes R and N, at a point not yet determined in the main sequence, we may have to fit in another branch containing stars showing bands of zirconium oxide, Class S

In the above paragraph, though we have followed the usual sequence of spectra and spoken of one set of lines developing and replacing others, there is no time sequence to be thought of as invariably accompanying the spectral sequence in one direction As we shall see in the following chapter, a view now widely held is of a double sequence from " late " to " early " and back to " late " classes again The subject of stellar evolution will be discussed in a later chapter

53 Adopted Classification —At the meeting of the International Solar Union held at Mount Wilson in 1910, a Committee was appointed on the classification of stellar spectra in the hope that the confusion arising from the use of the many existing systems might be ended The views of the members of the Committee proved, on inquiry, to be generally in favour of retaining the Draper classification as the basis of a system for universal adoption * This view was confirmed at the meeting, in 1922, of the International Astronomical Union at Rome The Harvard system was adopted for general use with modifications and additions to the notation where required for special technical researches We give below details of the Harvard classification as given by Miss Cannon in the Henry Draper Catalogue, † together with notes on some of the more important additions adopted by the International Astronomical Union For convenience

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* *Ap J* xxxiii 260 1911
† *Harvard Annals*, vols xci -xcix, 1918-24

of reference, Miss Cannon's classification of planetary nebulæ is added, but on this subject the reader is referred to § 66 below

54 Draper Classification—Class Pa   The double line 3726, 3729 is more conspicuous than the chief nebular lines 5007, 4959   Typical nebula, I C 418, R A 5 h 22 8 m , Dec — 12° 46′ [*Equinox here and throughout this paragraph 1900 0*]

Class Pb   The lines 5007, 4959 are stronger   Typical nebula, the Great Nebula of Orion

Class Pc   The line 4363 is the most conspicuous Typical nebula, I C 4997, R A 20 h 15 6 m Dec + 16° 25′

Class Pd   The chief nebular line 5007 is the strongest line Typical nebulæ, N G C 6826, R A 19 h 42 1 m , Dec + 50° 17′ and N G C 6326, R A 17 h 12 9 m , Dec — 51° 40′

Class Pe   The line *He* II 4685 7 is also present   Typical nebulæ, N G C 7662, R A 23 h 21 1 m , Dec + 41° 59′, and N G C 7009, R A 20 h 58 7 m , Dec — 11° 46′

Class Pf   A bright band centred at 4650, probably due to carbon, is the most conspicuous feature of the spectrum Typical nebula, N G C 40, R A 0 h 7 6 m , Dec + 71° 32′

Class Oa   A broad, bright band, centred at 4650, is the most conspicuous feature of the spectrum   Hγ and Hδ are bright, and several other bright bands are seen, but not the typical nebular lines such as 4363 or 5007   Typical stars, B D + 35° 4013, R A 20 h 8 2 m , Dec + 35° 54′ and C P D — 60° 2578, R A 11 h 5 8 m , Dec — 60° 26′

Class Ob   A wide, bright band, centred at 4686 is the most characteristic feature, the hydrogen lines Hβ, Hγ, Hδ, are bright, and also the helium lines of the ζ *Puppis* series (see Class Od below)   Typical stars, B D + 35° 4001, R A 20 h 6 5 m , Dec + 35° 53′ and C D M — 23° 4553, R.A 6 h 50 0 m , Dec — 23° 48′

Class Oc   The bands are narrower, and two well-separated lines are seen at 4686 and 4638, the former due to

ionized helium being twice as bright as the latter, due to ionized nitrogen (4634, 4642)   The hydrogen lines and the *ζ Puppis* lines are bright   No dark lines are seen   Typical stars, B D + 36° 3987, R A   20 h   13 3 m , Dec + 37° 7', and C D M — 41° 10972, R A   16 h   45 3 m , Dec — 41° 41'

Class Od   All lines are dark except 4686 and 4638, which are bright   Seven dark lines of the *ζ Puppis* series (ionized helium) at 5412, 4542, 4200, 4026, 3924, 3858, 3815 have been photographed, and the line *He* I 4471 5 is now seen   Typical stars *ζ Puppis* and *λ Cephei*   From here to the early Class A stars the dark hydrogen lines are paramount

Class Oe   This represents a transition stage from Pickering's Type V to Secchi's Type I   All lines are dark except *He* II 4686 and *N* III 4634, 4642, the two latter lines being the probable source of a bright band at 4638 , hydrogen lines and numerous helium and other dark lines are present, notably *Si* IV 4089 and *N* III 4097 *   Typical star, 29 *Canis Majoris*, R A   7 h   14 5 m , Dec — 24° 23'

Class Oe 5   Intermediate between Oe and Bo   No bright bands are seen, but the *ζ Puppis* series is present, and strong as in Class Oe   The lines *He* I 4026 and 4471 5 are strong as also the line *He* II 4686 , a line at 4650, probably *C* III, is strong   Typical star, *τ Canis Minoris*

Class Bo   The hydrogen lines strengthen, and the *ζ Puppis* series weaken   The lines *C* III 4647, 4650 are strong, and the triplet *O* II 4070, 4072, 4076 is growing in strength   The lines *Si* IV 4089, 4116, are at their greatest intensity   The lines *He* I 4026, 4471 5 are of equal strength, but less intense than the line at 4650, now probably a blend of oxygen and carbon   Typical star, *ε Orionis* (Alnitam)

Class B1   The Balmer series of hydrogen can be followed

* For the evidence that these lines are due to silicon atoms with three electrons removed and nitrogen with two electrons removed see Fowler   Report on Series in Line Spectra   p 164 (Physical Society of London 1922) *Proc R S* cui A, 413, 1923, and *Phil Trans*, ccxxv A, 1, 1924

up to Hτ The ζ *Puppis* series cannot be distinctly seen
Trebly ionized silicon, and doubly ionized carbon are fainter,
while helium grows stronger, *He* I 4471 5 exceeding *O* II 4649
in intensity, as also *He* I 4121 exceeds *Si* IV 4116   The
lines *Si* III 4552, 4568, 4574 are reaching maximum strength
Typical stars, β *Canis Majoris* (Mirzam) and β *Centauri*

Class B2   The lines of helium reach maximum intensity,
the trebly ionized silicon and the ionized oxygen lines are
much weaker, *Si* IV 4116 is not seen   Typical stars,
γ *Orionis* (Bellatrix) and α *Lupi*

Class B3   The hydrogen lines strengthen appreciably,
but the helium lines stand out prominently owing to the
disappearance or extreme faintness of the oxygen and
silicon lines   The strongest helium lines are 3820, 4009,
4026, 4144, 4388, 4471 5, and 4922   Typical stars, π^4
Orionis and α *Pavonis*

Class B5   *Ca* II 3933 7 [K] becomes stronger, as also
the double, *Si* II 4128, 4131, this double is now inter-
mediate in strength between the helium lines 4121 and
4144, the last-named being the strongest of the four lines
Mg II 4481 is 0 7 times as intense as *He* I 4471 5   Typical
stars, *q Tauri* and ϕ *Velorum*

Class B8   The lines *He* I 4026 and 4471 5 are present,
the latter being equal in strength with *Mg* II 4481   *Ca* II
3933 7 [K] is weaker than *He* I 4026   Several of the lines
due to ionized metals, prominent in Class A0 are present
Typical stars, β *Persei* and γ *Gruis*

Class B9   The spectrum is almost the same as that of
Class A0, except that *He* I 4026 is seen, and [K] is somewhat
fainter than in Class A0   Typical stars, λ *Aquilæ* and
λ *Centauri*

Class A0   The hydrogen lines are at maximum intensity,
[K] is about one-tenth as intense as Hδ *Ca* II 3968 5,
[H], is separated from Hϵ *Mg* II 4481 is next strongest
to [K] and the hydrogen lines   Many metallic lines are

present   The lines *Si* II 4128, 4131 are at maximum strength *   Typical star, *a Canis Majoris* (Sirius)

Class A2   [K] is nearly half as intense as Hδ   The lines *Mg* II 4481, *Ca* I 4227, *Fe* II 4233 are well marked, the two latter being of nearly equal strength   No helium lines are seen in this or any following class   Typical stars, δ *Ursæ Majoris* and *a Centauri*

Class A3   [K] is more than half as intense as the compound line, [H] and Hε, and is four-fifths as intense as Hδ   The metallic lines are more numerous and stronger than in Class A2, while the hydrogen lines are slightly fainter   Typical stars, *a Piscis Austrini* (Fomalhaut) and T³ *Eridani*

Class A5   [K] is now stronger than Hδ, and nearly as strong as the blend of [H] and Hε   *Mg* II 4481 is no longer the most conspicuous of the other lines   Lines at 4300, due to iron and ionized titanium and iron, are well marked   Typical stars, β *Trianguli* and *a Pictoris*

Class F0   The hydrogen lines are now about half the strength of those in class A0   [K] is as strong as [H] and Hε combined, and three times as strong as Hδ   The iron, titanium and calcium lines 4305-09 are faint and inconspicuous   Typical stars, δ *Geminorum* (Wasat) and *a Carinæ* (Canopus)

Class F2   The lines 4305 to 4315 increase in strength, suggesting a continuous dark band where, in later classes, we find the hydrocarbon [G] band   Typical star, π *Sagitarii*

Class F5   *Ca* I 4227, [g], is well marked among numerous lines, but it is not half as strong as Hγ , *Fe* 4326 is about one-tenth as intense as Hγ   The blend at 4309 is more intense than the iron and titanium blend at 4315   The hydrogen lines are twice as strong as in Class G0 (solar type), while the metallic lines are fainter and less numerous than

* Payne *H C O Circular* 252 1924

in Class Go   The band [G] is probably just present.
This Class represents the transition stage from Secchi's
Type I to Type II   The hydrogen lines are still predominant;
the typical star, α *Canis Minoris* (Procyon), was classed by
Secchi as Type I   The southern typical star is ρ *Puppis*

Class F8   Intermediate between Classes F5 and Go in
the strength of the hydrogen lines and a few of the metallic
lines   Otherwise it closely resembles Class Go   Typical
stars, β *Virginis* and α *Fornacis* (Zavijava)

Class Go   The solar type of spectrum   The hydrogen
lines no longer stand out conspicuously as a series   Hγ is
now only half as intense again as *Fe* 4326   The iron and
strontium blend at 4077, Hδ and *Ca* I 4227 are nearly equal
in intensity   The broad dark lines [H] and [K] are very
conspicuous   The continuous spectrum is nearly constant
in intensity from Hβ to Hε, but there is a slight gradual
falling off from Hγ to Hε   Typical stars, α *Aurigæ* (Capella)
and β *Hydri*

Class G5   The hydrogen lines are slightly fainter than
in Class Go   Hγ is now fainter than *Fe* 4326   The lines
Si I 3905, 4103 are at maximum strength   The distribution
of light becomes less even   Typical stars, κ *Geminorum*
and α *Reticuli*

Class Ko   The sunspot spectrum   The hydrogen lines
are fainter than in Class G5, Hγ being only half the intensity
of *Fe* 4326   The line *Ca* I 4227, [g], is three times as strong
as in Class Go and is three times as intense as the iron double
4383-5   The hydrocarbon band [G] is continuous from
4299 to 4315, and is more conspicuous than the line [g]
Several portions, such as 4077-Hδ, 4215-4227, 4470-4525
and 4614-4648 appear brighter than adjacent parts, and
the continuous shows a decided decrease from Hγ to Hε
The dark lines at [H] and [K] reach their greatest intensity
Typical stars, α *Bootis* (Arcturus) and α *Phœnicis* (Nair al
Zaurak)

Class K2 The calcium line [g] is stronger, but the [G] band is still continuous The continuous spectrum is fainter towards the end of shorter wave-lengths Typical stars, β *Cancri* and ν *Libræ*

Class K5 The most conspicuous lines are [H], [K], and [g] The [G] band is no longer continuous The two blends *Fe* 4383-5 and *Fe, Va,* 4405-8 form a conspicuous pair, the former being the stronger The absorption bands of Class M begin to appear in the form of breaks in the continuous at 4761, Hβ, 4955 and 5167 Typical star, α *Tauri* (Aldebaran) This class represents the transition stage to Type III

Class Ma or Mo * The spectrum is banded, the bands being due to titanium oxide † The strongest absorption bands have heads at 4762, 4954, 5168, 5445 Bright spaces are seen, such as 4556-4586, 4657-4668 Owing to the faintness of the continuous spectrum towards the shorter wave-lengths [H] and [K] are barely visible *Ca* I 4227, [g], is the most conspicuous absorption line The lines of the [G] band are well separated, and *Fe* 4315 is very faint Typical stars, α *Orionis* (Betelgeuse) and γ *Hydri*

Class Mb or M3 The edges of the absorption bands mentioned in the previous class are strong, and appear like bright bands *Ca* 4227 is very wide and intense Only blends at 4300 and 4306 remain well marked in the position of the band [G] Conspicuous bright bands show at 4556-4586, 4614-4626 Typical stars, ρ *Persei* and γ *Crucis*

Class Mc or M8 The continuous spectrum is fainter, and the bright-edged bands stronger, than in the two preceding classes The spectrum appears fluted Typical stars, W *Cygni* and R X *Aquarii*

* A modification approved by the International Astronomical Union at Rome, 1922

† Fowler, *Proc R S*, lxxiii 219, 1904 *M N R A S*, lxix 508, 1909

Class Md *   This class consists of stars of Class M, in which at least one hydrogen line is bright   It includes the greater number of the long period variables, though the spectra differ widely in detail   Typical stars, χ *Cygni* and o *Ceti* (Mira)

Class Ro †   This and the following classes belong to Secchi's Type IV   The distribution of light resembles that in Classes G5 or Ko, the broad absorptions at [H] and [K] being well seen   A dark carbon band at 4737 (centred at 4700) is wide and strong, and a dark blend (probably of titanium, vanadium, and iron) at 4395 is about equal in strength to the [G] band   The dark bands in this and the next few classes down to N3 are due to compounds of carbon There are well-marked lines at *Ca* I 4227 and at *Fe* 4234, 4236, and 4239   Typical star, S D − 10° 5057, R A 19 h 17 6 m , Dec − 10° 54′

Class R3   The [H] and [K] lines are visible, but fainter than in Class Ro, the continuous spectrum to the violet of Hγ being only about half as intense as for Class Ro   Typical star, B D + 5° 5223, R A 23 h 44 0 m , Dec + 5° 50′

Class R5   The continuous spectrum for wave-lengths shorter than 4240 is barely visible save for very long exposures   There are three bright regions of increasing intensity centred at 4300, 4400, 4840   Typical star, S D − 3° 1685, R A 6 h 56 1 m , Dec − 3° 6′

Class R8   The spectrum is very faint to the violet of 4240   The spectrum closely resembles that of Class No Typical star, B D + 61° 667, R A 3 h 57 2 m , Dec + 61° 31′

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* The International Astronomical Union proposes that this symbol should be replaced by the symbols Moe M1e M2e   M8e For details of this spectral class see Merrill *Pub of the Obs of the Univ of Michigan* ii 45 1916 and *Ap J* lviii, 215, 1923
    † See Rufus, *Pub of the Obs of the Univ of Michigan* ii 103, 1916

Class Na or No *   The spectrum between 4240 and [K] is even fainter than for Class R8   The three bright regions of Class R5, which have for that class respective intensities 3, 6, 10, have for class No intensities 0, 8, 10   Typical star, 19 *Piscium*, B D + 2° 4709, R A 23 h 41 3 m , Dec + 2° 56'

Class Nb or N3   We may estimate the respective intensities of the three bright portions found in the preceding classes as 0, 6, 10   Typical star, B D + 67° 350, R A 4 h 40 8 m , Dec + 67° 59'

Class S †   This class contains many long period variables and other red stars which resemble neither Class M nor Classes R and N   Absorption bands are present at 4650 and 6470, while the spectrum between 4500 and 4700 is very complicated with absorption and emission lines   The absorption bands have been identified with those of zirconium oxide   Most of the stars in this class have bright hydrogen lines, and they appear to represent a third branch of spectral sequence similar to the G — K — M and G5 — R — N branches   Typical stars, π 1 *Gruis*, R *Cygni*, and R *Andromedæ*

In connection with this account of the Draper Classification, taken from the Henry Draper Catalogues, it is convenient to make a few comments   The terms " early " and " late " are regularly used of stellar spectra referring to the positions of stars in the spectral sequence O — B — A — F — G — K — M   It is unfortunate that this custom was started when it was generally believed that this sequence corresponded to the order of evolution   The terms have proved very convenient and will probably remain in use as a method of dividing the spectral sequence into two portions   It must be remembered, however, in

* See Hale Ellerman and Parkhurst *Pub of the Yerkes Obs* , 11 251, 1903

† Merrill *Ap J*   lvi 457, 1922

this connection that they do not carry with them their usual time significance and do not correspond to early and late stages in the evolution of a star

A modification of the Draper Classification, which has been adopted by some writers, consists of the replacement of the Classes Oa, Oe, by classes with numerical affixes as in the rest of the scheme This will have to be done eventually from criteria based on the temperature or ionization of the stellar atmospheres A start has been made by H H Plaskett in his study of three O-Type stars * He rejects the Harvard sub-divisions of Class O in terms of bright bands, and suggests the substitution of criteria in terms of the presence or absence of certain dark lines His suggested scheme is as follows —

Class Oo The ionized helium lines found in ζ *Puppis* are not visible No typical star of this class is known

Class O5 The ζ *Puppis* ionized helium lines present and at their strongest relative to the Balmer series of hydrogen *He* II 4542 is o 6 times as intense as Hγ *N* III 4634, 4642 just seen Typical star, B D 35° 3930, R A 19 h 59 8 m , Dec + 35° 45′

Class O6 *He* II 4542 now half as strong as Hγ *He* I 4471 5 now seen, but not so strong as *He* II 4542 *Si* IV 4089 present, but weak and not so strong as *N* III 4097 Typical star, B D 44° 3639, R A 20 h 53 1 m , Dec + 44° 33′

Class O7 *He* I 4471 5 stronger than *He* II 4542, which is now only o 4 times as strong as Hγ *Si* IV 4089 strengthening compared with *N* III 4097, which is at its maximum strength *C* III 4647 now present Typical star, 9 *Sagittae*

Class O8 *He* I 4471 5 now twice as strong as *He* II 4542 and other *He* I lines at 4121, 4144, 4388, 4713,

* *Pub D.A O* , 1 325 1922 For a fuller study of O-Type stars see J S Plaskett, *Pub D A O* , 11 287, 1924

quite strong Si IV 4089, N III 4097, of equal strength, the silicon having strengthened and the nitrogen weakened The C III triplet at 4647 is stronger Mg II 4481 just appears Typical star, λ *Orionis*

Class O9 Lines generally sharper Si IV 4089, 4116 reach their maximum, while Si III 4552, 4568 are just appearing Mg II 4481 is stronger Doubly ionized carbon is stronger, but not yet at maximum strength The O III lines at 3962, 5592 are strong Helium is strengthening relative to hydrogen and still more relative to ionized helium Typical star, 10 *Lacertæ*

For Wolf-Rayet stars with bright lines, the Classes O5 to O9 may be used with the affix e to denote the presence of emission (see § 55 (9) below)

55 Notation for Special Spectra —The International Astronomical Union has adopted a number of modifications of the notation of the Henry Draper Catalogue in order to deal with special cases A few of these are given below

(1) Composite spectra should be denoted by the sign $+$ connecting the two superposed types, as Ko $+$ B9, the same notation being used for an eclipsing variable whose spectrum varies more or less discontinuously

(2) In the case of such stars as Cepheid variables, where the spectrum varies continuously, it should be recorded as, for example, " F7 to G4 " If one spectrum only is given for a variable star it should be the spectrum at maximum

(3) The prefix c should be used for exceptionally bright stars which normally have all lines narrow and sharp In the c-stars later than ‑Ao the hydrogen and the enhanced metallic lines are abnormally strong compared with their general spectral type Ca I 4227 is abnormally weak when compared with Hγ or with Sr II 4216 The stars should be called c-stars and the prefix should not be used for stars of class earlier than Bo Typical stars ϵ *Canis Majoris*, cB1 , α *Persei*, cF5 , and α *Scorpii* cMo

(4) The prefix g should be used for ordinary giant stars of Class Fo or later which have the enhanced lines and the hydrogen lines strong for their spectral type, and the low-temperature lines relatively weak   For Class F *Sr II* 4077 and 4216, *Ti II* 4290 are strong, for Classes G, K, M *Sr II* 4077 and 4216 are strong, *Ca* I 4227, 4435, and 4456 are weak   Typical stars, *θ Scorpii* gFo, *η Piscium* gG5, *α Bootis*, gKo and *β Pegasi*, gM3

(5) The prefix d should be used for faint dwarf stars of Class Fo or later   The lines above-mentioned show reversed relative intensity to that of the giant stars, low temperature lines, including *Ti* 4535, weak in the giants, show up as strong for the dwarfs and vice versa   In Class F *Sr* II 4077, 4216, and *Ti* II 4290 are weak   In Class M *Sr* I 4607 is strong Typical stars, *α Canis Minoris*, dF5, *μ Herculis*, dG5, 70 Ophiuchi (Br), dKo, and *Lal* 21185, dM3

(6) It is recommended that standard or typical spectra should be chosen from among the giant stars, preferably of absolute magnitude about 0 or 1 (except for Class B, where they must necessarily be brighter)   This would involve such substitutions as *v Persei* for *α Canis Minoris* in Class F5

(7) Spectra showing all lines unusually wide or diffuse should have the affix " n," and those showing sharp lines without the c-characteristics should have the affix " s " For instance *α Leonis* would be B8n   The letters " n " and " s " qualify the preceding symbol

(8) The symbol " k " is proposed for stars with special stationary lines, such as [H] and [K] and the [D] lines Typical star, *δ Orionis*, Bonk

(9) Bright lines should be denoted by the letter " e," * except in classes whose definition involves the presence of bright lines   Cases where the bright lines are conspicuously

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* This is the reason for replacing class Md by the class Me sub-divided according to the nature of the absorption spectrum into sub-classes M1e M2e, etc

reversed with a dark centre would be denoted by " er," while, if the bright lines are bounded on the violet side by absorption lines, the letters " eq " are suggested It is also suggested that where some of the hydrogen series—starting from the red end—are bright, the letter α, β, etc , should be added, to indicate which is the last visible bright line Typical stars, γ *Cassiopeiæ*, Boe , P *Cygni*, B4eq , and α *Cygni*, cA2eα

(10) The letter " p " is reserved for miscellaneous peculiarities, and it should be used to qualify the symbol immediately preceding The same rule should apply to the symbols " n " and " s "

The final notation for the spectra of gaseous nebulæ has not been settled, but it is important to distinguish where possible between the spectra of the nucleus and of the surrounding envelope

The letter Q is suggested for novæ, with a series of letters to indicate the presence of certain simple types of spectrum or types of associated spectra Here, again, the final details are not yet worked out It should be pointed out once more that the Draper classification of § 54 suffices for ordinary use, and that the modifications and additions of the present paragraph will chiefly be of use in special technical investigations They do, however, offer a means of conveying, in brief compass, very useful additional information as to a star's spectrum

CHAPTER IX

GIANT AND DWARF STARS

56 The Single Line of Evolution —At the end of
the nineteenth century, and for the first decade of
the twentieth century it was fairly generally believed
by astronomers, with a few notable dissentients, that
the sequence of spectral classes followed above, namely
P — O — B — A — F — G -- K — M (or G — R — N),
represented the normal line of development of the stars
from planetary nebulæ The words " early " and " late "
applied to this sequence also applied to a star's position in
the evolutionary time-scale In favour of this view were
facts of the following nature There is a complete sequence
of spectra from the gaseous nebulæ to the red stars, and the
great majority of the stars can be placed at some definite
point in the sequence The sequence was made first of all
from the appearance of the spectra, but laboratory experi-
ments showed that it corresponded to a gradually changing
physical condition, which has been interpreted in terms
of temperature or ionization The sequence appeared to
represent an order of progressively lower temperature or
decreasing ionization for the stellar atmospheres A single
line of development was similarly indicated by Campbell's
result * that the radial velocities of stars changed steadily
along the sequence of the above scheme The only excep-
tions were the planetary nebulæ which came at the wrong

* Stellar Motions, p 207 1913 see also § 46 above

122

end of Campbell's table   (We now know that Class Oe stars are also exceptions)

Still further evidence pointing to the same order of development was supplied by Campbell * from a study of the periods of spectroscopic binary stars   Two-thirds of the binaries of Classes O and B that he examined had periods less than 10 days , half the Class A and half the Class F binaries had periods less than 10 days , no known binaries of Classes G, K, M (with one possible exception) had periods of less than 20 days   All this evidence suggested the same single line of development   So, also, did the distribution of the stars in the sky   " Early " stars are concentrated in the galaxy, and there is a tendency for stars of " later " type to diverge more and more from the galaxy   Altogether a very considerable body of consistent evidence had been brought together, all pointing to the same simple line of evolution, the chief outstanding difficulty lying in the early stages of the scheme, the direct transformation from the original nebulæ to the hottest stellar types

57 The Two-Branch Theory of Evolution —On the theoretical side Ritter,† following Homer Lane,‡ and on the observational side Sir Norman Lockyer,§ steadily maintained that it was essential that any evolution scheme must provide for a branch of ascending temperature as well as for a branch of descending temperatures   Instead of one single line of development from the hot stars of Class O down to the red stars, this alternative scheme starts with an extended mass of gas at low temperature and allows for an increase of temperature as the gas contracts—it is, in fact, a scale of *increasing density*, and stars of a given

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* ' Stellar Motions, p 261
† *Annalen der Physik*   eighteen papers in vols v -xx 1878-83
‡ *American Journal of Science*, l 57 1870
§ *Proc R S* , lxv A, 188, 1899, lxxiii A, 227, 1904   lxxvi A 145 1905

spectral type may belong either to the branch of increasing temperature or to the branch of decreasing temperature The scheme is no longer to be represented as

P O B A F G → S / M K R N

but as

B
A → A
F → F
S →→ G   G ← S
K R   R K
M   M
N   N
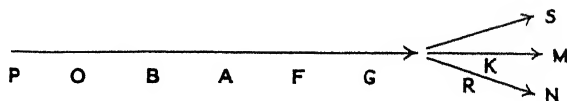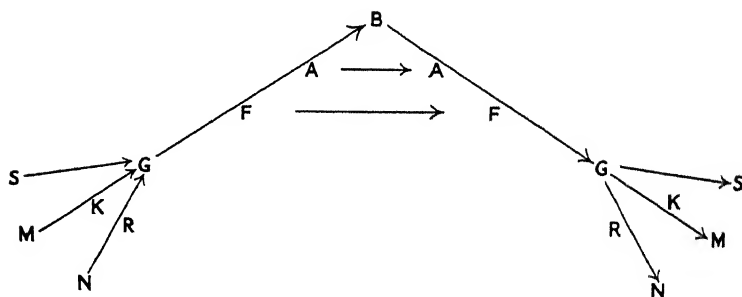
FIG 4

The course of evolution sketched by Ritter starts with a widely extended nebulous mass of gas of very slight mean density With loss of heat by radiation the mass contracts and a slow increase of density is accompanied by a rise in temperature As the density increases, the heat from the centre escapes less readily by radiation and we reach a culmination of light intensity at which the effectively radiating layer is only a small fraction in depth of the whole radius of the star The quantity of heat radiated per unit area now diminishes, although the surface temperature increases for a time, the maximum of radiation shifting slightly to the violet After the second culmination, that of maximum temperature, has been reached, both the total radiation and the surface temperature diminish rapidly, the star ceasing to obey the gas-laws owing to increasing density

Several difficulties prevented the general acceptance of the views of Ritter and Lockyer For one thing, evidence

had been steadily accumulating (as explained in § 56 above) which pointed to physical changes accompanying a single sequence of spectra   Again, not sufficient differences were recognized among stars of the same spectral class to justify the view that they formed two groups differing so much in density and pressure as was required by Ritter's theory   (In this Lockyer dissented from the views generally held)   Further, the spectroscopic link recognized as existing between the planetary nebulæ and the hot O and B stars was lacking between the nebulæ and the cool red stars   There was no evidence connecting nebulæ with the giant red stars of the branch of ascending temperatures   To some extent these difficulties have since been removed   For instance Merrill has found * in the spectrum of R Aquarii, a red variable star of type Md, the bright lines at 4363, 4658, 4959, 5007 which are typical of nebular spectra, as also, the helium line 4471 which occurs in nebulæ   Slipher at Flagstaff Observatory, has photographed this star, and finds it † to be surrounded by a nebulous envelope   Here, then, is one definite link between a red variable star and a nebulous mass of gas and, though too much stress must not be placed on one case, the objection that *no* link between the nebulæ and red stars has been found, has vanished   Again, Adams, in his work on spectroscopic parallaxes has definitely established detailed differences ‡ in the spectra of the stars of high and low luminosity—the giants and dwarfs—of the same spectral type   And Russell, Hertzsprung, and others, have collected a mass of explicit evidence which shows that for the later type stars we do get the same general spectrum accompanying stars of widely different luminosity and density , we do find the two groups of red stars required by Ritter and Lockyer

58 Giants and Dwarfs —As observational data increased

* *Ap J*   liii 375, 1921   † *Observatory* xlv 100 1922
‡ See § 60 below

it was found that by whatever criterion stars were examined in the separate spectral classes, the late type stars fell into two very different groups (Plate 25)   Thus Hertzsprung,* from a study of proper motions, found that the red stars formed two groups of very different luminosity, which were subsequently called " giant " and " dwarf " stars   Russell, from a study of parallaxes,† confirmed this differentiation, and supported the suggestion that the essential difference lay in density and in surface area   We have already seen (§ 36 above) that late type stars have colour indices which separate out into two well-defined groups   For a given spectral type, the giants are redder or have lower effective temperatures than the dwarfs, or we may say that for a given temperature the giants are of earlier spectral type than the dwarfs   This is because the spectral type, defined by the relative strengths of different absorption lines, depends on the degree of ionization in the absorbing layer of the star's atmosphere, and this depends only partly upon the temperature, but partly, also, upon the gravitation at this layer ‡   Theory and observation agree as to the direction in which the difference of colour-index between the two classes should occur   Again, a study of the absolute magnitudes and spectra of double stars of known orbits gave clear evidence of the separation of giant and dwarf stars among the later spectral types and enabled Russell to tie the great difference in brightness definitely to a difference of superficial area rather than of mass , § and the fact that for giant binaries the fainter star—generally the less massive one—is usually of earlier type, while for dwarfs it is usually of later type,‖ is consistent with Russell's

* *Zeit f Wiss Photographie*, iii 429, 1905, and v 86, 1906
† *A J* xxvi 147 1910
‡ Pannekoek, *B A N* , No 19, 115 1922 , R H Fowler and Milne, *M N R A S* , lxxxiv 508, 1924
§ *Observatory*, xxxvi 328 1913
‖ Leonard, *Lick Obs Bull* , No 343, 188, 1923

PLATE 25
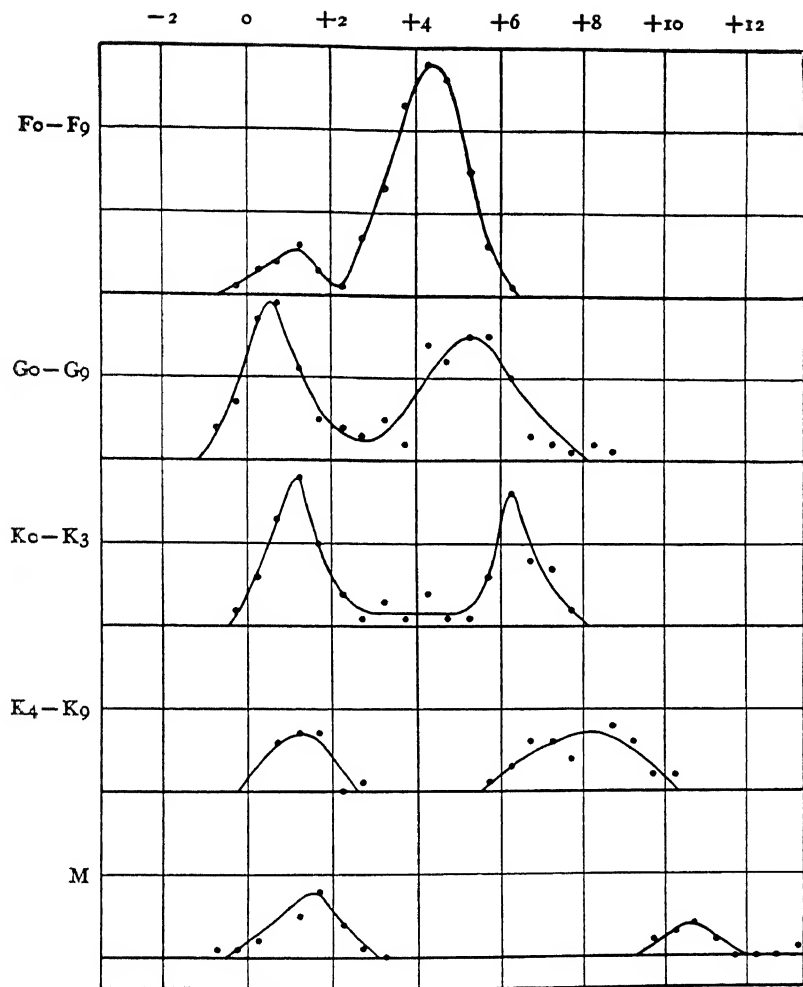
FREQULNCY-CURVES OF ABSOLUTE MAGNITUDES FOR DIFFERENT SPECTRAL
TYPI S   ADAMS'S STUDY OF SPECTROSCOPIC PARALLAXES, 1917

theory, under the simple assumption that the less massive star passes through its development more rapidly than its more massive companion   We have seen (§ 39 above) that there are very good reasons for believing that the masses of stars all fall within a fairly narrow range , it is density and superficial area that vary greatly rather than mass But, as we have seen, the mass of a star in radiative equilibrium is a controlling factor in determining its temperature and spectrum   In Russell's theory, as first stated, the temperature determined by a star's mass might be taken to be the highest temperature reached by the star in its evolution up the branch of ascending temperature   Only the most massive stars would reach the B Class, others moving across from the branch of ascending temperature to the descending branch at Classes A, F, and so on, according to their masses , the less massive stars would change over at lower temperatures than the more massive stars (Stars of less mass than one-seventh the sun's mass would never rise to a temperature at which they would become visible to us)

59 Mass and Evolution —It is on the close connection between a star's mass and its luminosity (and indirectly its spectrum) that the most recent speculations on stellar evolution depend   If we regard the course of evolution as so slow that the great bulk of the stars, even the dense dwarfs, may be considered as being in radiative equilibrium, then we must cease to regard the sequence of stellar spectra as necessarily representing successive stages in stellar evolution   Each star is in equilibrium and has the absolute magnitude and spectrum appropriate to its own mass   We have no knowledge of the stages through which it passed before it reached stability, we have no clear view of the future stages through which it has yet to pass   Only when we assume that the fundamental variant, the mass of a star changes in some definite way, can we once more sketch out

a scheme of stellar evolution   Recent speculation has examined this point too

We are no longer content with Kelvin's view that the sun's radiant energy is supplied by the loss of gravitational energy consequent upon contraction   Contraction is not capable of supplying anything like sufficient energy to suit the time-scale of the modern cosmogonist or of the geologist   Some fresh source of energy must be found to supply the outgoing radiation, and modern theory has found this in the connection between mass and radiant energy   The theory of relativity has shown that, if energy dE escapes from a body as radiation, the mass of the body must diminish by dE$/c^2$ where c is the velocity of light   Thus energy of radiation is obtained from the actual annihilation of matter, by the destruction of electrons and protons   We come back to the idea that the star is burning itself away, radiant energy replacing mass

The old single line of evolution, or the branch of decreasing luminosity in the two-branch theory of evolution, will fit into the new order of ideas quite satisfactorily, the only change being to replace increasing density by decreasing mass as the main evolutionary factor   It is not so easy, however, to determine the position and fate of the giant stars of low temperature   Until we have had further knowledge of the connection between a star's mass, the rate of generation of sub-atomic energy and the resulting internal and effective temperatures, it is idle to speculate on the course which such a star will follow   Statistical considerations suggest that the red giant follows along the sequence of ascending temperature of the two-branch theory, its temperature increasing while its luminosity decreases , this fits in with Coblentz's estimate * that the average absolute luminosity of the red giants is greater than that

* *Scientific Papers of the Bureau of Standards   Washington* No 438 1922   See also a table and figure by Danjon *L Astronomie,* xxxv 425 427, 1921

of the yellow giants, but it is inconsistent with Adams's result that at the other end of the sequence, for A and B stars, the earlier types are the more luminous   More data on the statistical distribution of the masses and temperatures of giant stars must, however, become available before we can place the branch of ascending temperatures once more in a secure position as part of the scheme of stellar evolution   One curious point will even then await explanation and that is the nature of the mechanism which nearly equates the rate of production of sub-atomic energy in the interior of a star to the rate of outflow of radiation   How do these two disparate quantities so nearly balance as to leave the star apparently in a stable condition, subject only to a very gradual secular change ?

60 Spectroscopic Parallaxes —The study of giants and dwarfs leads naturally to an examination of the minor differences between the stars of similar spectral type which differ markedly in luminosity   Russell first showed that a relationship existed between a star's luminosity and its spectrum   In the skilful hands of Adams at Mount Wilson,* this relationship led to the determination of stellar distances from a study of stellar spectra   Having used the relative intensity of hydrogen and iron lines for an accurate classification of stellar spectra—the Harvard scheme was adopted with careful grading between classes—a careful study was made of two stars of the same spectral class and of known parallax, which differed considerably in luminosity   Thus $\alpha\ Tauri$ (K5) and $61^1\ Cygni$ (K7) have absolute magnitudes 0 4, 8 0 respectively, or the former is 1100 times as luminous as the latter   Adams found that low temperature lines, such as $Ca\ I$ 4435 were stronger in $61^1\ Cygni$, while enhanced spark lines, such as $Sr\ II$ 4216, were stronger in $\alpha\ Tauri$ The varying behaviour of these two lines for stars of high

* $Ap\ J$ xl 385, 1914   xlvi 313 1917 , liii 13, 1921 $Proc$ $N\ A\ S$, ii 143 1916

and low luminosity was found to persist through a wid
range of spectral types   With the aid of a number o
stars of known parallaxes and magnitudes, numerica
relations were established between the absolute magnitude
of the stars and the difference in the intensity betwee
the pair of lines considered (Plate 26)   When the differenc
of intensity was plotted against the absolute magnitude th
graph came out as a straight line for stars of spectral type
Fo to K4—thus the difference of intensity of the selecte
pair of lines was a linear function of the absolute magnitude

We need not follow in detail the various steps by whic
Adams extended, checked, and made good his method o
determining absolute stellar magnitudes from a study o
spectra   It will be enough here to mention the lines h
finally adopted as keys to stellar luminosity and the deduc
tions as to giant and dwarf stars

For the range of spectrum Fo-F5 the pairs chosen were

Lines Strong in Stars of Low Luminosity	Lines Strong in Stars of High Luminosity
Fe I 4072	Sr II 4077
Fe I 4250	Sr II 4216
Fe I 4271	Ti II 4290

For the range F5-K8

Fe I 4250	Sr II 4216
Ca I 4456	Fe I 4462
Ca I 4456	Fe I 4495

For the range K8-M

Ca I 4456	Sr II 4077
	Hδ
	Fe, V I 4207
Sr I 4607	Sr II 4216
	Hγ

The accompanying figure (Plate 25) shows plainly ho
Adams's criteria divide the later type stars clearly into tw

PLATE **26**
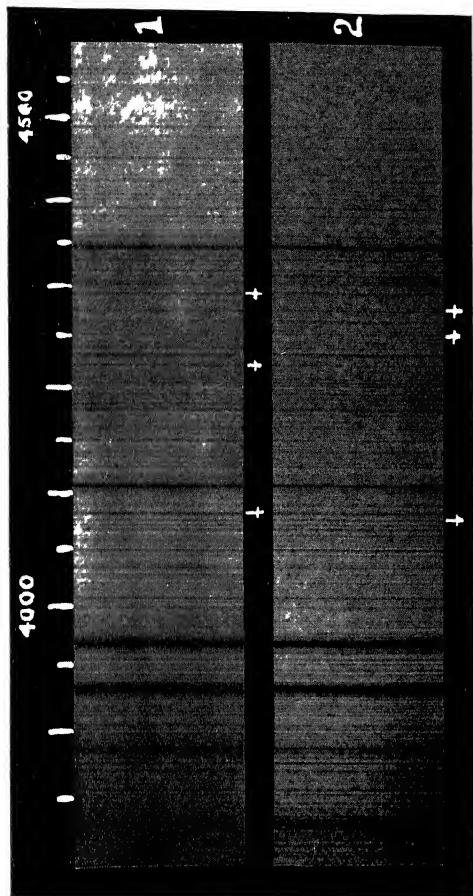
1 ν *1 ERSEI*—GIANT
2 α *CANIS MINORIS*—DWARF } SPECTRUM F5

Spectrograms taken at the Norman Lockyer Observatory   The lines strengthened in each star are indicated by +

classes, the giants and the dwarfs The work of Adams finally disposes of the objection that stars of very different physical condition could not show spectra fundamentally alike and differing only in small details Adams's earlier work has been followed by investigations at other observatories Fresh pairs of comparison lines for stars of high and low luminosity of types Fo to Mb have been taken into use * Further, an extension has now been made to include in the scheme the hotter stars of Types A and B Thus Adams and Joy † have found that among A type stars those with sharp and narrow lines are more luminous than those of the same spectral type with diffuse lines They also found that the average luminosity of the stars increased steadily from absolute magnitude 2 6 at A9 to 1 0 at A0 (diffuse lines) Both these results have been confirmed by G Abetti ‡ The steady increase in luminosity continues through the B type spectra, the average absolute magnitude for Bo (diffuse) being − 3 1 § Edwards,‖ by a method more in accord with Adams's earlier work, showed that for B stars the absolute magnitude could be determined by the relative intensities of certain lines of helium and hydrogen, the helium being relatively weaker for the stars of greater luminosity This result seems inconsistent with the fact that He I lines are at maximum strength at Class B2, while the H lines are at maximum at A0 The apparent anomaly is, in large part, due to the fact that the relative strength of some He I lines and the H lines are taken into account

* Rimmer *Memoirs R A S* lxii 113 1923 lxv 1 1925 *H C O Circ*, 228, 1921, 232, 1922, 243 1923 Young and Harper *Journal R A S, Canada* xviii 9 1924 *Pub D A O* iii 1 1924

† *Proc N A S* viii 173 1922, and *Ap J* lvi 242 1922

‡ *Pub del R Inst di Studi Sup in Firenze Fascicolo* No 41 1924

§ *Pub A S P*, xxxv 120 1923 and *Ap J* lvii 294, 1923

‖ *M N R A S*, lxxxiii 47, 1922

in classifying the star What is measured by Edwards is a secondary effect

Deslandres * and Burson have suggested a further spectral difference between giant and dwarf stars They have found evidence for bright chromospheric lines [H_2] and [K_2] in the upper atmospheres of several giant stars of types G, K, and M (Plate 27) For these stars they have found that the bright lines are broader with increasing luminosity and much broader in the case of the giant stars than in the case of the sun, a dwarf Here we may find ultimately a valuable clue in our analysis of the differences between the spectra and the density gradients of the atmospheres of giant and dwarf stars

It is, perhaps, worth repeating here that, what the difference in the spectra measures directly is not the absolute luminosity (L) of the star, but really the gravitation at its surface It is this which mainly affects the degree of ionization in the atmosphere for a given temperature † It is because $g \propto \sigma M/L$, where σ, the surface brightness, is constant for a given class, while M, the mass, varies only slightly compared with the enormous accompanying changes in L, that we get so good a measure of a star's absolute luminosity from a study of its spectrum

* *C R* clxxv 121 1922
† Pannekoek, *B A N* No 19 115 1922

PLATE 27
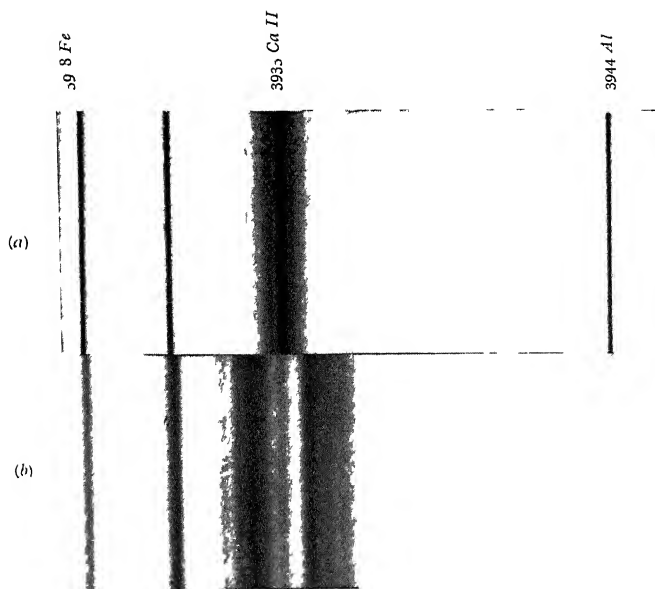
(*a*) SPECTRUM OF THE SUN WITH A HIGH DISPERSION TO SHOW $[k_2]$, $[k_3]$

(*b*) SPECTRUM OF ARCTURUS, A GIANT STAR OF CLASS k0, SHOWING $[k_2]$, $[k_3]$

Spectrograms were secured at Meudon by H Deslandres   In the original spectrum of Arcturus the distance from | H | to | K | is 4 mm   The dispersion in the case of the solar spectrum was 5 times as great   Both spectrogram are given here reduced the same scale

PLATE 28
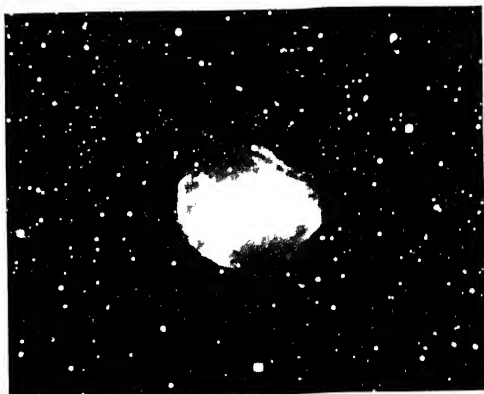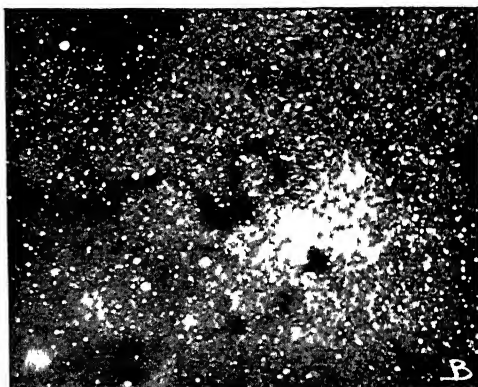
(a) THE "DUMBBELL NEBULA"

Photographed with the 2 ft reflector of the Yerkes Observatory

(b) DARK MARKING NEAR θ *OPHIUCHI*, $\alpha = 17$ H 16 M 17 S, $\delta = -23° 37'$

Photographed by Barnard with the Bruce telescope at the Yerkes Observatory

NEBULÆ

61 Main Types —There are to be found many masses
in the sky consisting of a glowing gas of unknown nature ,
these often show a stellar nucleus and may represent the
pre-natal condition of a star   As already stated, the evi-
dence for a link between these nebulous masses and the red
giant stars is limited to the case of R Aquarii, a red variable
star surrounded by a gaseous envelope which shows bright
nebular lines in its spectrum   These bright line nebulæ, very
varied in appearance but with fairly defined boundaries,
are called *planetary nebulæ* (Plate 28)   To study the many
curious forms found, the reader is referred to the magnificent
volume on nebulæ recently published by the Lick Observatory
—*Publications of the Lick Observatory*, vol xiii

Diffuse in appearance and thoroughly irregular in shape
come the *diffuse irregular nebulæ*   Some of these are
shown by the bright lines in their spectra to consist of the
same type of gas as is found in the planetary nebulæ, though
the matter is here not condensed round central nuclei   For
other diffuse nebulæ the spectrum is continuous with absorp-
tion lines   There is some relation * connecting the spectrum
of a diffuse nebula and those of the stars which seem to be
most clearly associated with or involved in it   The nebulæ
with bright line spectra are connected with stars of earlier
type than the stars connected with nebulæ with absorption

* Hubble, *Ap J* lvi 162 400 1922

spectra   Though these nebulæ do not shine with reflected light from the stars it looks as though their luminosity was excited by light from the star   The sequence runs from a planetary nebula excited by a hot Wolf-Rayet stellar nucleus, through a diffuse nebula with continuous spectrum excited by B type stars, down to an opaque or dark nebula which has not been excited to luminosity

There are known in the sky many dark lanes and patches which may be *dark nebulæ* (Plate 28), perhaps irregular nebulæ which have not yet reached, or have passed, the physical condition in which they become visible   Barnard * made a special study of these dark markings and gave very good grounds for the view that they consist of dark screening matter between us and the background of stars rather than that they are mere gaps in the grouping of the stars as seen from the earth

The planetary nebulæ are concentrated near the galaxy The most important class of nebulæ, the *spiral nebulæ*, show a marked aversion to the plane of the galaxy   These nebulæ will be discussed below   Here we must mention that the spectra of these nebulæ are generally absorption spectra, frequently of solar type   The integrated spectrum of the Milky Way † is of the same nature, a fact which lends support to the suggestion that the spiral nebulæ are very distant aggregations of stars, like the Milky Way   Some of these spiral nebulæ also show bright nebular lines in their spectra ‡   These may come from the presence in the spiral nebulæ of enormous patches of bright nebulosity, such as we find in the Magellanic Clouds   Reynolds § has suggested that the light of spiral nebulæ is due to reflected light from a central star or nucleus   This suggestion applies mainly

* *Ap J passim* in particular, xlix 1, 1919
† Fath, *ibid* xxxvi 362 1912
‡ Fath *ibid* xxxiii 59, 1911
§ *M N R A S* lxxii 553 1912

to nebulæ whose condensation into separate stellar masses has not proceeded too far, and it should be considered in connection with Hubble's suggestion of the excitation of light in diffuse nebulosity by stellar sources of intense radiation

The Clouds of Magellan, with some hundreds of nebulous objects and star clusters, resemble the Milky Way in many respects They offer the only part of the sky outside the galactic regions where stars and nebulosities with bright line spectra are found in profusion The clouds, both by reason of their appearance, and also by reason of the high radial velocities—averaging + 276 km /sec *—of the nebulæ which lie in them and move with them should probably be classed with the spiral nebulæ

62 Radial Velocities —We have already seen (Table V above) that the planetary nebulæ have a large average radial velocity, a fact that would place them near the dwarfs rather than near the giants in the evolution scale The average radial velocity for 31 stellar planetary nebulæ after allowing for the solar motion relative to the brighter stars, is 28 km /sec , the average for 65 non-stellar planetary nebulæ is 31 km /sec ,† while the average for the Class B stars is only 6 km /sec There is obvious difficulty in regarding the planetary nebulæ as the direct forerunners of the main body of the Class B stars, especially when we realize how few of the former are known—about 125 in all (but see Chapter XIV below) But planetary nebulæ share the high radial velocities with Class O stars These two classes of bodies do seem to be organically related The average radial velocity of the diffuse gaseous nebulæ is only 11 km /sec , which seems to differentiate them from the planetary nebulæ on the one hand and from the spiral nebulæ on the other These nebulæ may be

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* *Lick Obs Pub* , xiii 189, 1918   † *Ibid* , 173, 1918

related to the stars of Class B   V M Slipher has found *
an average radial velocity of approximately 600 km /sec for
41 of the spiral nebulæ, the highest velocity observed being
+ 1800 km /sec   The great majority of these velocities are
positive, indicating a general recession of spiral nebulæ from
the sun or rather from the galaxy, if the displacement of the
spectral lines is to be ascribed to velocity alone

Attempts have been made to explain the recession of the
spiral nebulæ in several ways   De Sitter,† in accordance
with his theory of relativity, has explained the displacement
of the spectral lines to the red as being due, in part, to a
general tendency for particles to scatter and in part to
the slowing down of atomic vibrations of distant objects
Lindemann would account for the recession of the spiral
nebulæ as being due to light pressure from our galaxy, the
nebulæ being, in his view, clouds of dust shining by reflected
light from the galaxy ‡   Neither explanation can be accepted
as satisfactory, and the large displacements of the spectral
lines in the spiral nebulæ remain a perplexing and unsolved
problem

63 Internal Motions in Gaseous Nebulae —Campbell and
Moore, in their study of the spectra of the bright line nebulæ,
have investigated the evidence for internal motions   For
more than half the objects examined, the spectral lines have
indicated internal motions in the nebulæ   For many of
these cases the simplest interpretation appears to be that the
nebulæ are rotating about axes approximately perpendicular
to the line of sight, the highest rotational speeds being found
for the most elongated planetary nebulæ   In addition, a
certain number of planetary nebulæ, mainly those which
show the ionized helium spectrum, have the principal
nebular lines doubled over their central portions   This

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* Eddington   The Mathematical Theory of Relativity ' p 162,
1923
† *M N R A S* , lxxviii 28, 1917   ‡ *Ibid* , lxxxiii 354 1923

doubling may be due to a reversal of a broad bright line by outer layers of cooler gas, it may be due to a central expansion or contraction of the nebula as a whole (velocities of the order of 30 km/sec are indicated), or, again, it may be in some way, of atomic or sub-atomic origin On the whole, one of the first two explanations is the most likely In addition to the doubling of nebular lines found by Campbell, Slipher and Sanford have shown that certain nebulæ have lines doubled to an extent that would require much higher internal velocities, namely, of the order of 500 km/sec if the doubling is to be explained in terms of velocities In confirmation of this explanation comes the announcement by Slipher that photographs of the Crab Nebula give evidence of internal movement, relative displacements of well-marked nuclei having been measured * The subject is ripe for further investigation

64 The Distances of the Spiral Nebulæ —In a recent series of papers † van Maanen has compared recent photographs of some of the larger spirals with earlier photographs, and has studied the motions of definite condensations in the arms relative to the stellar background As Jeans foretold on theoretical grounds,‡ the motions discovered are outward along the arms of the spiral, the velocities generally increasing with distance from the centre The hypothesis of outward motion along the arms agrees better with the observations than the hypothesis of simple rotation of the nebula as a whole It has this difficulty, however The time taken for matter to do one complete circuit round the nucleus is on the average less than 100,000 years and the two arms of the spiral show too few convolutions for the nebula to be more than several hundred thousand years old In terms of the time-scale now generally adopted for the sidereal

* *Observatory* xlii 322, 1919 xliv, 160, 1921
† See, among others *Ap J* xliv 210, 1916 lvii 264 1923
‡ *Observatory* xl 60, 1917

universe, this makes spiral nebulæ as a class improbably young and we are driven to the view that the arms of nebulæ disperse into stars accompanied, probably, by a great mass of invisible dark matter   There is not a great deal of evidence for dark matter surrounding such spiral nebulæ as are so placed that we see the spirals openly and well (Plate 29) In this case, however, the presence of bright condensations surviving along with the dark matter might disguise the phenomenon   For spiral nebulæ placed edge on to us there is a considerable body of evidence as to occulting matter in the outer regions *   In fact, the presence of such matter seems to be the rule rather than the exception   And this together with the presence of dark lanes between the bright whirls of the spiral nebulæ seems to fit in with the views as to their evolution developed by Jeans   According to one view, the spiral nebulæ are at enormous distances, and may be regarded as of the same size and nature as the galaxy   The size of the proper motions observed in them would mean such enormously high internal velocities that any comparison with the galaxy would be out of the question   The idea of spiral nebulæ as island universes, offered first by the elder Herschel and revived periodically by later investigators, seemed to have received a very heavy blow in this work of van Maanen   More recently, Hubble from a study of the light-curves of 12 Cepheid variables in the Andromeda nebula has derived for it the enormous distance of 950,000 light-years †   Hubble's results would give impossibly high values for the velocities of the nuclei determined by van Maanen, and it would appear that these motions are illusory   The theory of the island universe has been restored to favour once more

65 The Nebular Spectrum —The first spectroscopic examination of a nebula was made by Huggins in 1864, when he turned his telescope on the planetary nebula in Draco

* See *Lick Obs Pub* xiii Plate III
† *Popular Astronomy* xxxiii 143 252 1925

PLATE 29
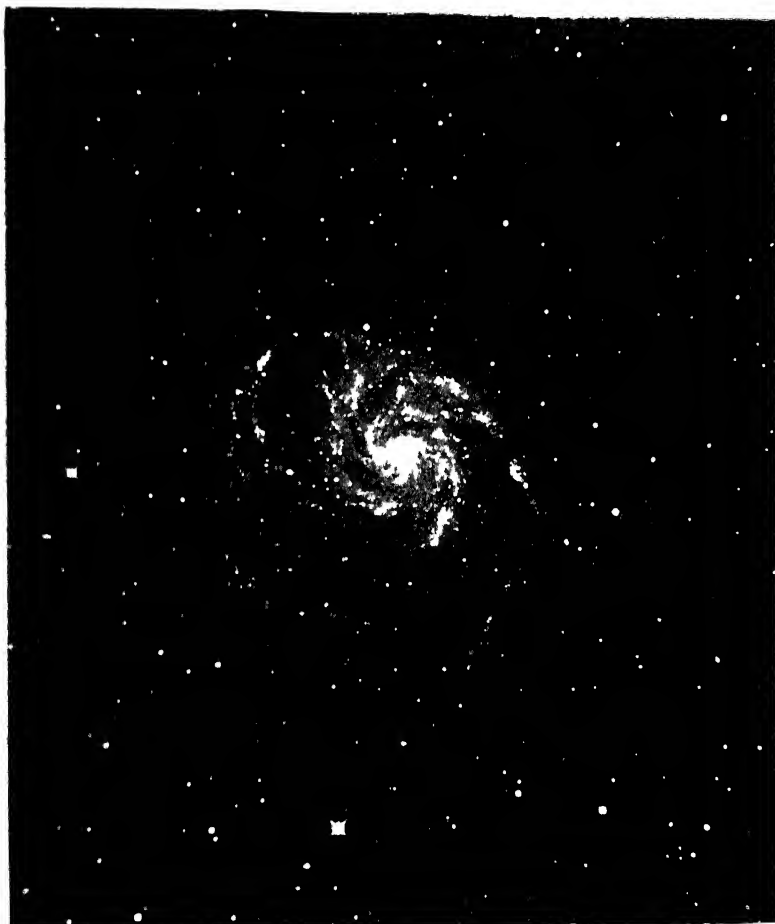
MESSIER 101

Photographed with the 24 inch reflector of the Yerkes Observatory

His own account * is worth repeating, if only for the spirit that it reveals —

" I looked into the spectroscope   No spectrum such as I expected !   A single bright line only !   At first I suspected some displacement of the prism and that I was looking at a reflection of the illuminated slit from one of its faces   This thought was scarcely more than momentary , then the true interpretation flashed upon me   The light of the nebula was monochromatic   a little closer looking showed two other bright lines towards the blue   The riddle of the nebulæ was solved   The answer which had come to us in the light, itself, read   not an aggregation of stars, but a luminous gas "

This discovery came at an opportune moment when the resolutions of so many nebulæ into clusters of stars by Lord Rosse's great telescope had led to the idea that all nebulæ were mere close aggregations of stars   The work of Keeler at the Lick Observatory, and later of W H Wright at the same observatory, has given us a nebular spectrum with many more lines than the three seen by Huggins   These three were the two principal nebular lines $[N_1]$ and $[N_2]$, at 5007 02 and 4959 09 respectively, together with the hydrogen line $H\beta$

The bright lines found in nebular spectra include the Balmer series of hydrogen, lines of ionized helium, nitrogen and carbon, familiar in the stars of Classes O and B, and, in addition, a number of lines of unknown origin due, perhaps, to some unknown element   At least two elements seem to be involved   Nicholson † found that he could tie together the wave-lengths of most of the lines in terms of the periods of vibration of a model atom with nucleus $+ 4e$, and with one ring of 4 electrons for the neutral atom   The accuracy of

* Scientific Papers of Sir William Huggins, ' vol ii 106 1909
† *M N R A S*, lxxii 49 1911 and see § 22 above for similar work on the coronal spectrum

fit of spectrum to model is not as close as in the case of the coronal spectrum, but there is good agreement save for a few outstanding lines   One of the lines originally left out of his scheme by Nicholson was the ionized helium line at 4685 7, which was subsequently discovered in the laboratory by Fowler in 1912 *   Other lines outstanding from Nicholson's scheme were the lines 3726, 3729, for which Buisson, Fabry, and Bourget later claimed a different origin from that of the line 5007 0   Their method depended on measuring the widths of the lines of the spectrum   Assuming the widths to be due to the velocities of the atoms of the gas—a somewhat rash assumption, as we know now—it was possible by the kinetic theory of gases to deduce the temperature of the nebula and the atomic weights of the gases concerned The temperature of the Orion nebula came out at 15,000°, and the atomic weight of the gas giving the doublet at 3727 came out at about 3, and that of the gas giving the line 5007 0, came out somewhat lower †   That the doublet at 3727 differs in some very significant way from the principal nebular line has been strikingly demonstrated by Wright ‡ (Plate 30)   The distribution in certain nebulæ of the gas giving this doublet is very different from that of the gas giving the principal nebular line   The presence of two elements, or of one element in two distinct physical conditions, is indicated

The best table of the wave-lengths of the spectral lines found in the nebulæ is given by Wright §   The lines vary in relative strength from nebula to nebula, especially when compared with the hydrogen and helium lines   These

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* The line had been seen on some laboratory plates taken at South Kensington in 1898 (*Proc R S* lxxiv A, 545, 1905)   It was first isolated in a helium vacuum tube by Butler in 1909

† *Ap J* , xl 257 1914

‡ *Lick Obs Pub* xiii Plates XLVIII, L

§ *Ibid* Table II, and see Appendix VIII below for the chief lines

PLATE 30
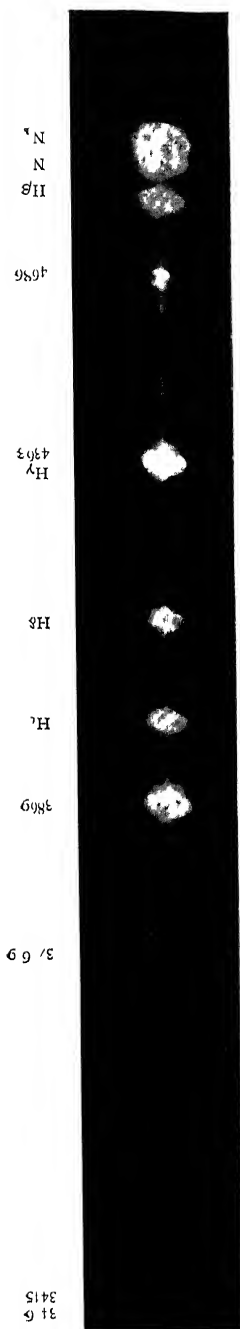
(a) N G C   7009
(b) N G C   7662

Slitless spectrograms of nebulæ taken by W. H. Wright at the Lick Observatory

variations in intensity have been adopted as the test for use in classifying the spectra of the nebulæ But, before this classification is discussed, mention must be made of one very significant fact The nuclei of many planetary nebulæ show the spectra of Wolf-Rayet or Class O stars, while the outer envelopes have the more typical nebular spectrum Thus, at the other end of the temperature scale from R Aquarii we have frequent illustrations of stars with nebular envelopes There is, however, just this difference between the two cases The evidence points to planetary nebulæ with stellar discs as expanding, whereas nebulosity connected with red giant stars is generally assumed to be contracting

The extension of the continuous spectrum of the nuclei of planetary nebulæ into the extreme ultra-violet also calls for mention * It is not impossible that this extension of the continuous spectrum is due to high thermal excitation and may indicate a temperature higher than that found for any ordinary stars , it is more probable, however, in view of a similar phenomenon in the spectrum of the prominences and a connection between one edge of this continuous spectrum and the limit of the Balmer series, that the spectrum is due to hydrogen, in some condition of excitation not yet repeated in the laboratory

66 Spectral Classification —It is not possible as yet to lay down with any confidence the order of evolution, if any, connecting (a) Class O stars having no nebulous envelope , (b) planetary nebulæ with Class O nuclei , and (c) planetary nebulæ without nuclei The older views on stellar evolution would undoubtedly make the order (c), (b), (a) leading on to the Class B stars The more recent views do not include the planetary nebulæ in their general scheme of evolution Possibly certain Class B stars, perhaps the most massive,

* See *Lick Obs Pub* , xiii 256, 1918

instead of developing along the line of descending temperature, rise still further in temperature into Class O, then, some kind of instability sets in and nebulous matter is driven forth by some process which ultimately dissipates the whole stellar nucleus. That this is not the only possible line of development for planetary nebulæ we shall see below in the chapters on novæ and cosmogony. According to some writers, planetary nebulæ are to be regarded as the wrecks of new stars which have, in the past, blazed suddenly up in the heavens

The Draper classification (see § 54 above) depends mainly on the relative intensity of certain lines, notably 5007, 4959, 4686, 4363, 3729, and 3726. The difficulty of adopting this classification lies partly in the fact that different lines vary considerably in relative strength at different points in the same nebula. Wright suggests * in his investigation of the details of nebular structure, the following scheme —

Class I, 4686 present in the *nebula*
    (*a*) 3426 stronger than 3445
    (*b*) 3445 stronger than 3426
    (*c*) Both 3426 and 3445 absent
Class II, 4686 absent from the *nebula*, but 3869 present, with sub-classes according to the strength of 3869
Class III, 4686 and 3869 both absent

The shape and structure of the nebula and the relations of the nebular to the nuclear spectrum must also be taken into account. When the clue as to the formation and development of nebulæ has been found, it is probable that shape and structure will be found to play a prominent part in any evolutionary classification

* *Lick Obs Pub* xiii 262, 1918

CHAPTER XI

NOVÆ

67 Historical Novæ —The earliest reference to a new or temporary star appearing in the sky is to be found in the Chinese records of Ma-tuan-lin * The first star so recorded was in the year 134 B C , and it is said by the elder Pliny † to have led Hipparchus to complete his star catalogue —

" Ideoque ausus rem etiam deo inprobam, adnumerare posteris stellas ac sidera ad nomen expungere organis excogitatis per quae singularum loca atque magnitudines signaret, ut facile discerni posset ex eo, non modo an obirent ac nascerentur, sed an omnino aliquæ transirent moverenturque, item an crescerent minuerenturque, caelo in hereditate cunctis relicto, si quisquam qui cretionem eam caperet inventus esset "

The most famous new star in the pre-telescopic days was the star of 1572, which attracted back to astronomy the great Danish pioneer—Tycho Brahe This star in the constellation Cassiopeia was said to be brighter than Sirius or Jupiter at its brightest , it was seen in daytime and remained visible to the naked eye for fifteen months With greater telescopic power available, with an increased number of observers watching the skies with accurate charts available for comparison, it is natural that the frequency of discovery of new stars should have increased We may note that four new stars have been observed with the naked eye in the course of the present

* *Connaissance des Temps* 1846 61
† *Naturalis Historia,* Bk II, Ch 26

century   Nova Persei—in the accepted notation N Persei 1901—was discovered at Edinburgh by the Rev T D Anderson at 14 h 40 m G M T , on 21st February , having already had the good fortune to find one nova—N Aurigæ 1892—this observer was on the look-out for another, and he secured his second find as the result of much faithful searching   At discovery, Nova Persei was of magnitude 2 7 Twenty-seven hours earlier, it was definitely fainter than 11 0 m , thirty-eight hours after discovery it had reached a magnitude of 0 1   After this, it decreased in brightness, fairly rapidly at first, then more slowly, with a series of oscillations in brightness   The accompanying changes of spectral type will be discussed later   Nova Geminorum— N Geminorum 1912—was discovered by Enebo, at Dombaas, in Norway, when studying red variables in a special region of the sky   Its magnitude at discovery was 4 2, and the evidence from the Harvard photographs was that the star's brightness had increased by 6 5 magnitudes at least in the preceding twenty-three hours   The maximum reached was 3 4, after which the star slowly faded, again with marked fluctuations   Both the above stars have contributed to our knowledge of the spectra of novæ, but the star which promises to give the greatest amount of information on the origin and development of novæ is N Aquilæ 1918, discovered casually by many observers as of magnitude 0 8, on 8th June, 1918   This star had apparently been known for thirty years as a slightly variable star of about magnitude 10 5   In the course of four days it blazed up to a magnitude of − 1, becoming, for a short time, the brightest star in the northern sky   Its light curve followed much the same course as those of the two preceding stars   The last naked-eye nova, N Cygni 1920, was discovered by the veteran meteor observer, W F Denning, at Bristol, on 20th August, 1920, when at magnitude 3 5   This star increased more slowly than usual in the case of novae to its maximum brightness,

1 8 m , but on the other hand it faded more rapidly and
steadily after passing its maximum   In spectral develop-
ment these four novæ followed the same general line of
development as had been observed for N Aurigæ 1892
The later stars, however, gave far more detail, and the
following paragraph is based mainly upon observations of
them

68 Spectral Development —The study of recent novæ
has given what appears to be the normal sequence of changes
in the spectra of novæ   If observed early enough, while
brightening, the star appears like an early A Class star (or
a B Class star in the case of N Persei 1901) with the dark
lines all displaced to the violet   The elements most strongly
represented are generally hydrogen and ionized iron, titanium
and calcium   The displacement varies as the wave-length
and suggests motion of the absorbing gases towards the
observer, the velocity of approach increasing or decreasing
from day to day   The fact that the displacement always
implies motion towards the observer is best explained by
the fact that the absorbing gases form part of a jet, pulse,
or shell of gas moving out from the centre of disturbance
when intervening between an observer and the star so as
to show absorption lines on a bright continuous background,
such outflowing gases must necessarily always be seen
approaching the observer

The second stage observed shows the presence of bright
companions on the red side of the absorption lines   These
bright companions rapidly broaden, and often show complex
structure with several maxima   Their centres are approxi-
mately at the normal wave-length of the line identified with
the absorption companion   When lines are crowded together
in the spectrum the broad, bright bands are cut into by
other dark lines, and the structure spoilt   Some of the lines,
notably the hydrogen lines and a few of the enhanced
metallic lines, next show a second dark companion which

10

is more displaced than the first, still in the direction of shorter wave-lengths   At this or some still later stage, these more displaced companions may be accompanied by dark lines corresponding to the carbon, oxygen, nitrogen, and helium lines prominent in Class B stars (Plate 31)   We may have present in the same spectra an absorption spectrum of Class A, displaced by an amount corresponding to a velocity of — 800 km /sec , and an absorption spectrum of Class B, displaced as by a velocity of — 1800 km /sec *   In addition, there may be broad, bright bands present for one or both spectra and a further complication may be introduced by the presence of a spectrum of narrow, undisplaced absorption lines   The ionized calcium lines [H] and [K], and the ordinary [D] lines of sodium are commonly so found, and in the case of N Geminorum 1912 many ionized iron and titanium lines were also seen as undisplaced, narrow absorption lines on the bright bands of the spectrum †   At this stage the fading star is probably oscillating in brightness and in spectrum, the maxima corresponding to a stronger A Class spectrum and the minima to a stronger B Class spectrum   As the continuous spectrum fades away, and with it the A Class spectrum, a stage is reached where the star's spectrum appears to be almost wholly a bright band spectrum   Then we may have the following curious phases accompanying changes in stellar brightness   at light maxima—representing stronger continuous spectrum—we find strong absorption lines , at light minima strong, bright bands

The bright metallic bands representing the Class A spectrum are the first to disappear and, as they go, they are replaced by broad, bright bands corresponding to the nebular lines   Fluctuations in brightness accompany

* See *Annals of the Solar Physics Observatory, Cambridge*, iv 47, 1920

† *Ibid* , 52

PLATE 31

THE SPECTRUM OF NOVA GEMINORUM 1912

Photographed at the Cambridge Observatory March 15 April 29 1912

No 1 Mar 15

~ 15

3 20

4 22

5 6

6 8

7 10

8 Apr 1

9 3

10 8

11 29

12 May 30
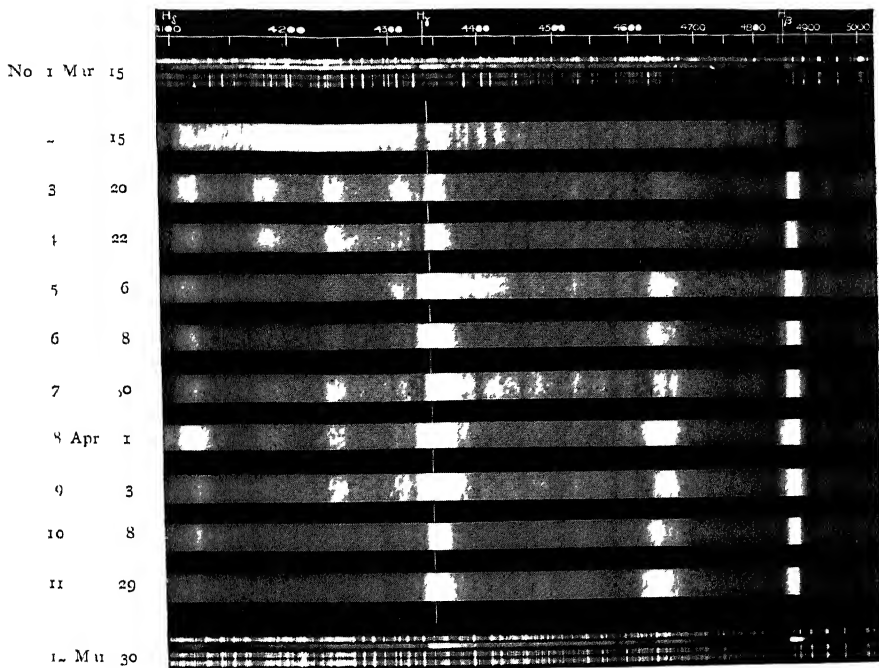
Nos 1 and 12 are stationery enlargements showing the comparison spectra of iron   Nos 2 to 11 have been widened by rocking

On No 2 are seen many broad bright bands and narrow absorption lines   In Nos 3 4 5 and 6 the bright and dark hydrogen pairs have a wider structure and are doubled

The stronger absorption lines in Nos 2 3 and 4 are mostly hydrogen lines or enhanced lines of iron and titanium characteristic of *a Cygni*   In Nos 7 and 9 the strong absorption lines other than the hydrogen lines are nitrogen oxygen and helium lines typical of *γ Orionis*   These are more displaced than the enhanced metallic lines but with the same displacement factor as the more displaced component of the pair of dark hydrogen lines

changes of spectra, the bright bands of Classes O and P being found for fainter stages than the bright bands of Class B   The nebular bands have a common structure very much resembling the structure of the hydrogen bands, whether these latter bands be examined at this stage or at an earlier stage   With some reservations it may be said that the intervals in the structure of the band vary directly as the wave-length of the corresponding line   Motion in the line of sight is still indicated as the best clue to the structure, though no simple scheme of jets, shells, or pulses fits all the facts *   It would be tempting to try and develop some explanation in terms of atomic structure, Stark effect or Zeeman effect, but one very important fact points markedly towards a Doppler effect   Shane and Moore † have shown that when the nova develops, as it appears to do generally, into a visible disc, some of the maxima in the bands come mainly from one part of the disc and some from another part of the disc   A complex system of rotations is indicated as a very important factor in producing the structure in the bright bands

The final stage towards which nearly all novæ seem to tend is that of a Class O star of varying brightness   Recent evidence suggests that this Class O star is surrounded by an expanding nebulous disc, and it looks as though a nova reaches a not uncommon form of planetary nebula with a nucleus of spectral Class O   It has even been conjectured that the great majority of planetary nebulæ, and possibly some Class O stars also, sharing, as they do, the same galactic distribution, are the wrecks of novæ of past ages   It may be that from some of the complex forms of these nebulæ we may be able to work back to the movements found in the early stages of novæ, and that each type will, in turn, help to the understanding of the other

* See Wright, *M N R A S*, lxxxi 191 501, 1921
† *Lick Obs Bull* No 322 1919

69 Novæ and Nebulæ—N Aurigæ 1892, six months after its first outburst, was discovered to have brightened to a second lesser maximum, and to be showing broad, bright bands in its spectrum in the position of the principal nebular lines, since then, this development of a bright nebular spectrum within a few months of discovery has been found to be typical of novæ   The exact connection between a nova and a gaseous nebula is not yet clear Ritchey, photographing the region round N Persei 1901 eight months after its appearance, found traces of nebulosity round the nova which later photographs showed to be moving rapidly outwards *   A study of the spectrum of this nebulosity by Perrine † showed that it resembled that of the nova at its stage of maximum brightness, this fact, coupled with considerations of the distance of the nova and the speed with which the nebulosity appeared to grow outwards, has led to the general view that what was photographed by Ritchey was the spread outwards of illumination from the central body, lighting up existing nebulosity Similar results have not been found for any other nova as yet, but this connection of the outburst of N Persei 1901 with surrounding nebulosity should provide a most important clue in building up a theory of the origin of novæ

The spreading bright nebulosity, which was observed in 1902, reaching to a distance of 20' from N Persei 1901, was, in all probability, not directly responsible for the nebular spectrum, it seems reasonable to attribute this spectrum to a much smaller nebular envelope which was discovered by Barnard in December, 1916, nearly sixteen years after the first discovery of the star, ‡ this nebulosity is nearly symmetrical round the stellar nucleus, and is apparently spreading outwards—having extended to a radius of over 8″ by 1920   N Persei 1901, within twenty years of dis-

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* *Ap J* xiv 293, 1901   xv 129 1902
† *Ibid* xvii 310 1903   ‡ *M N R A S* lxxx 721, 1920

PLATE 32

East
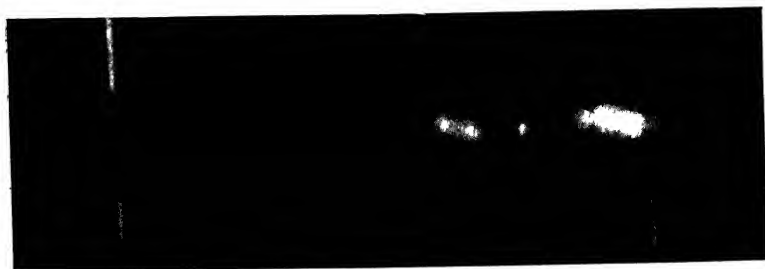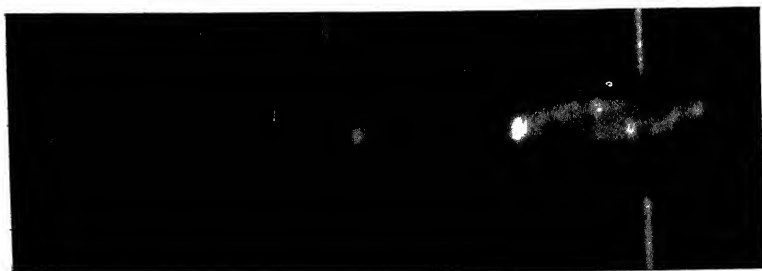
North

North

GREEN NEBULAR BANDS OF NOVA AQUILÆ, 1918, IN LATER STAGES

(a) 1919 August 1 slit in position ang e 112°
(b) 1919 August 1 slit in position angle 112°
(c) 1920 May 23 slit in position angle 202°

covery, had all the appearance of a typical planetary nebula —an unexpectedly rapid development when the usually accepted time-scale for stellar evolution is considered

This smaller and later display of nebulosity spreading out from the central disturbance, has been paralleled by the spreading discs found for the two most recent bright novæ, N Aquilæ 1918, and N Cygni 1920 We have here almost certainly the outward spread of actual matter from the centre , we may note that the rates of growth of the discs taken in conjunction with the probable parallaxes of the novæ give velocities for the outward flowing gases which are consistent with high velocities of about 2000 km /sec given both by the absorption lines in the early spectra and by the maxima in the subsequent bright bands This is one of the important arguments in favour of an interpretation of the complex spectra of novæ in terms of a simple Doppler effect Other disturbing conditions are undoubtedly present, but the outward flow of gaseous matter is one of the most important factors in producing the observed results

70 The Later Stages of N Aquilæ 1918 —An extraordinarily interesting addition to our knowledge of the later spectra of novæ was made by Moore and Shane in the case of N Aquilæ 1918 Observing the nova with a slit set across the visible disc at a certain angle and the disc kept fixed on a given point of the slit, they discovered * that certain bright maxima in the spectrum are strong in one part of the disc and others strong in other portions of the disc (Plate 32) Roughly speaking, maxima displaced by equal amounts from the normal position of the corresponding spectral line are bright on opposite sides of the disc If there were only two maxima, a simple interpretation in terms of two rotating arms would at once suggest itself But the phenomenon is more complex than that Rotations in opposite directions in the same plane are involved,

* *Lick Obs Bull* , No 322, 1919 , *Observatory* xliii 283, 1920

and further difficulties arise from the fact that the growing
disc is twice as large for the nebular lines as for the hydrogen
Two years after discovery, the diameter of N Aquilæ 1918
was 3″ 7 for the green nebular lines, but only 1″ 5 for Hβ
It is tempting to relate the outward growth of the disc with
the maxima in the bright bands   But, while equal veloci-
ties are indicated for the nebular gases and for hydrogen by
the displacements of the bright maxima, yet the two discs
grow at different rates   As is to be expected in such catas-
trophes as occur when novæ are born, no simple explanation
meets the facts   But as the disc of N Aquilæ 1918 grows,
and the structure opens out and becomes visible, we ought
to obtain some information of the greatest value from the
study of slit and slitless spectrograms

71 Theories as to the Origin of Novæ —It has been
suggested above that planetary nebulæ with Wolf-Rayet
stars as nuclei represent the ultimate fate of novæ   What
is to be said about their origin ?   What is the nature and
cause of the catastrophe which results in the outburst of
a new star ?   Three main lines of explanation have been
offered   The simultaneous presence of the dark and bright
line spectra naturally led to the suggestion of two stars
colliding or passing so close to one another as to produce
violent upheavals through tidal causes   The constant
repetition of a dark line spectrum on the violet side of the
accompanying bright band spectrum, the complicated
structure of the bands—suggesting the need for more than
two bodies—and the frequency of observed outbursts have
all told against the explanation of novæ in terms of two
colliding stars   The special form of this explanation
adopted by Bickerton in which the two stars leave a glowing
mass at the centre of disturbance, a mass shorn off the
colliding bodies in their partial impact, has likewise failed
to secure general acceptance

The view that in a nova we see the outburst of im-

prisoned energy through a breakdown in the stability of the crust of a cooling star, fails to suggest a sufficient cause for the enormous forces at work, say, in N Aquilæ 1918, or for the growing disc of the later stages of the nova It fails, also, to account for the distribution of the novæ in the sky the region of the galaxy, the Magellanic clouds and a few spiral nebulæ include nearly all known novæ

A clue that must not be overlooked is the nebulosity seen round N Persei 1901, illuminated by the light of the great initial outburst A further clue may be found in the shapes of the planetary nebulæ which seem particularly likely to have developed from novæ These are often helical and suggest a combination of rotation and translation in the source of the disturbance Though no simple theory yet worked out in detail offers an explanation of novæ, the most hopeful line of attack would seem to be the study of the phenomena accompanying the collision of a star or a binary star system, with an extensive nebulosity Seeliger * and Halm † have developed this theory, but so many new facts have been learnt since they wrote on the subject that their work requires to be greatly supplemented The final theory of novæ has not yet been developed, but the most likely solution at present available seems to be in terms of the spreading out of streamers of glowing gases from a central body or bodies after a collision with a dark cloud

72 Variable Nebulæ—Confirmation of the explanation of novæ suggested above may be found in the variable nebula N G C 2261, studied by Hubble ‡ and Brown § The latter has suggested that the fan-shaped appendage of this nebula with its rapid and irregular variations in light-giving power can be explained in terms of the passage of a

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* *A N* , cxxx 393, 1892 , *Astronomy and Astrophysics*, xi 904 1892

† *Proc R S Edinburgh*, xxv 513 1904

‡ *Ap J*   xliv 190 1916   § *Ibid* , liii 169, 1921

star—the head of the fan—through a nebula consisting of a swarm of particles   In this connection it is suggestive that the spectrum of the nebula * is a bright-line spectrum, consisting mostly of hydrogen lines and lines due to ionized iron, familiar in the early stages of novæ , further, the bright hydrogen lines are accompanied by dark companions on the violet side, as is the case with novæ   This variable nebula, and one or two others of like behaviour, are found in parts of the sky where there are dark spaces and accompanying diffuse nebulosity †   If this comparison and Brown's theory do have an application to novæ, it would seem that in these special cases the low relative velocity of the star and the cloud is mainly responsible for the absence of the great outburst of activity associated with novæ   The nucleus of each of these nebulæ varies in brightness   This is quite natural if the nucleus is a star passing through nebulosity of varying density and the brightness of the nebulosity would vary also , there is, however, an alternative suggestion which must be mentioned, namely, that the variation of the nebula is directly connected with varying radiation from the stellar nucleus to which its own luminosity may be due (see § 61 above)

   * Slipher *Lowell Obs Bull* No 81 1918   See also § 80 below
   † Knox Shaw *Helwan Obs Bull* , No 20 196 1920

CHAPTER XII

VARIABLE STARS

73 Classification of Variable Stars   Eclipsing Variables
—The classes in which variable stars may be grouped are
many   For the present the International Astronomical
Union has decided to maintain the five classes adopted by
E C Pickering *   (1) Novæ , (2) Long Period Variables ,
(3) Irregular Variables, generally with small range in magni-
tude , (4) Short Period , (5) Algols, or Eclipsing Variables,
which undergo for a short time with great regularity a
marked diminution in brightness   We have already dealt
with the novæ at some length   Long period and short
period variables are treated in the following paragraphs

Eclipsing variables are naturally closely connected with
spectroscopic binaries (see Chapter VII above)   Here we
need only mention that the shape of the light curve when
compared with the radial-velocity curve, gives a good indi-
cation as to the nature of the system   We are able to
determine from the light curve alone the relative sizes and
brightness of the two stars, the eccentricity of their orbit
round one another, the nature of the eclipses (whether
partial or total) and even, with certain reasonable assump-
tions, the amount of darkening at the limbs of the two
components and the elliptical shape of the stellar discs
With a knowledge of the velocity-curve we can get the

* *Proc of the American Academy of Arts and Sciences* xvi 17
1880

actual dimensions of the orbit and of the component stars *
The general results found have been that for a range of
variation of over one magnitude, the fainter star is larger
and redder than its companion For smaller ranges of
variation, the two stars are more frequently nearly equal
in magnitude The gravitational elongation of the stars
along the line joining them comes out in very fair agreement
with Darwin's theoretical value for a homogeneous, incom-
pressible fluid † Further suggestions made by Dugan ‡ to
improve the fit of the observed light-curve to the calculated
curve are that the sides of the stars turned towards one
another are brighter than those turned away from each
other, and also that the advancing side of the brighter or
eclipsing star is brighter than the following side What is
probably an unusual type of eclipsing variable, β Lyræ, is
dealt with in the next chapter (§ 82)

74 Irregular Variables—It is naturally not easy to
classify the irregular variables There are, however, two
or three groups which deserve special mention There are
twelve stars which resemble R *Coronæ Borealis* in that they
remain of constant magnitude for long intervals of time, but
are subject to occasional sudden drops in brightness of un-
certain amount (sometimes through several magnitudes) and
of uncertain date and duration The spectra of this group
of stars generally include bright lines, in several cases resem-
bling novæ at an early stage In R *Coronæ Borealis* the
hydrogen lines are absent from a spectrum of Class F5, this
being possibly a transition stage between bright and dark

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* See Russell and Shapley On Darkening at the Limb in Eclip-
sing Variables, *Ap J*, xxxvi 239 385, 1912 and Shapley The
Orbits of Eighty-Seven Eclipsing Binaries—a Summary ' *Ap J*,
xxxvii 158 1913

† *Phil Trans* ccvi A 161 1906

‡ *Contributions of the Princeton Univ Obs* No 2, 42 1912,
No 4, 22, 1916

hydrogen lines   Ludendorff has suggested * that the loss of brightness may be due to the passage of the star behind patches of nebulosity and the bright lines in the spectra may be connected with passage through a nebular cloud One of the stars in the group T *Tauri* has been found to lie in faint nebulosity to which the bright lines in its spectrum are probably due †   The whole group lie in low galactic latitudes

Another group of seven irregular variables, with U *Geminorum* as typical star, is to be found in a wide range of galactic latitudes ‡   These stars keep at constant or nearly constant brightness save for occasional rapid increases in brightness—through an average of four magnitudes and in a few days   The return to the normal brightness is slower, the light curve resembling that of a nova, except for the smaller range of magnitude concerned   The spectrum of two of them is known   In each case it is a variable spectrum of Class F with occasional bright lines present and a suggestion of two spectra blended together   In view of the position of these stars in space, something in the nature of a prominence outburst on a large scale rather than collision with nebulosity would seem to be indicated as the cause of the brightening

There is a small group of variable stars, called by Ludendorff the RV *Tauri* class,§ which have secondary oscillations in their brightness, though these secondary oscillations are not in constant phase-relation with the principal oscillations as in the case of eclipsing variables   These stars appear rather to link on through a small group of stars, of which R *Centauri* is typical, to the ordinary long period variables of Class M   In R *Centauri* the maximum is divided into two by a secondary minimum

75 Long Period Variables—The great majority of the

* *A N* ccix 273, 1919   † Pease *Ap J* xlv 89, 1917
‡ *A N* , ccxiv 221, 1921   § *A N* , ccxiv 217, 1921

long period variables have a range in brightness of about five or six magnitudes, and a period of about a year   They rise to light-maximum more rapidly than they fall to light-minimum   They have a continuous spectrum containing numerous absorption lines and bands due to chemical compounds, those of titanium oxide (Class M) being much more commonly found than those of zirconium oxide (Class S) or carbon bands (Classes R, N)   Bright lines are superposed on this absorption spectrum, the lines varying in brightness with different phases of the light-curve   The typical star of Class M is *o Ceti* or *Mira*   Amongst the bright lines are the Balmer lines of hydrogen (Hδ being frequently far the most conspicuous line), and low temperature arc lines of iron, magnesium and silicon , * there are curious indications of a few lines due to ionized metals †   The particular selection of bright lines found has yet to be explained by laboratory experiment, as also the peculiar variations in intensity of the hydrogen lines ‡   The absorption bands increase in intensity, as the star fades, while the bright lines of the different elements and even lines of the same element reach their maximum intensity at different stages of the light-curve §   The hydrogen lines are the first bright lines to appear, shortly after light-minimum , they reach maximum brightness shortly after light-maximum for M stars (and shortly before light-maximum for N stars) , the bright iron and magnesium lines appear later in the light-period, and reach their maximum intensity at different phases, the

* Stebbins *Lick Obs Bull*   No 41, 1903   Adams and Joy, *Pub A S P* xxx 193 1918

† *Cf* the 9^{m}0 companion to Castor also o^2 *Eridani*-C, both of which have bright [H] and [K] on an Me spectrum   *Pub A S P* , xxxii 158 1920 and xxviii 323 1921

‡ In the case of *o Ceti* some of the anomalies are to be explained by the presence of a faint companion of spectrum B8ep with bright lines due to hydrogen and ionized metals

§ Merrill *Ap J* liii 185 1921

magnesium line at λ 4572 reaching maximum brightness not long before light-minimum The marked faintness of several of the bright hydrogen lines is best accounted for by their being lost in strong absorption lines, e g Hε is very faint on account of its lying within the strong calcium absorption line [H] This, however, does not explain all the anomalies in the relative brightness of the lines of the Balmer series

We have already seen that in the case of the long-period variable R *Aquarii*, certain of the well-known nebular lines have been found bright,* such as 5007, 4959, 4658, 4363, 3869, and also the helium line, 4471 These lines remain constant in brightness throughout the period, and are apparently accompanied by constant bright hydrogen lines, on which are superposed bright hydrogen lines varying with the brightness of the star The hydrogen lines of constant intensity follow the nebulæ in their relative brightness, Hβ being stronger than Hδ It seems reasonable, in view of the discovery of surrounding nebulosity to ascribe these constant lines to a nebular envelope which has been photographed and found not to share in the fluctuations in brightness of the stellar nucleus R *Aquarii* also shows bright at minimum the low-temperature magnesium line λ 4572, in this, as in other respects, resembling the long-period variables of Class M

An interesting application has been made of the vacuum thermo-couple in studying the total radiation from *o Ceti* at different stages of the light curve † The total radiation changed in amount considerably less than the visual radiation, probably because the visual region of the spectrum lies on the violet side of the wave-length of maximum energy of the radiation A small shift of the maximum would mean a large drop in the apparent brightness, which

* Merrill *Ap J* liii 375, 1921
† Nicholson and Pettit *Pub A S P*, xxxiv 132 1922

affords an explanation of the large range in magnitude in the low-temperature variables   The use of a water-cell in front of the thermo-couple helps in the determination of the distribution of the spectral energy and of the corresponding stellar temperatures   Milne * has given a preliminary estimate of the range of temperature of o *Ceti* as 3000° at maximum, to 1700° at minimum

It has been pointed out by several writers † and con firmed by Ludendorff ‡ from the latest material available that the period, the amplitude of variation and the spectral type of the long-period variables are closely related   The range of variation increases with the period, and at the same time the star's spectrum is of later type §   It is not easy to say whether the presence of bright lines in the spectra, which distinguishes the stars of Class Me (or Md) from Classes M0, M3, M8 (or Ma, Mb, Mc), affects the period It is true that, on the whole, the Me stars are of longer period, but this is largely accounted for by the fact that later type stars are more frequent among the Me stars than among the M stars which show no bright lines   Nearly all the Ṁ variables with periods of over 400 days are Me stars

The Me stars are probably all giants,‖ and it would not be surprising if their periods differed from those of dwarf M stars, but the usual separation into two classes has not yet been made by the criterion of period

Another factor which varies with the period is the displacement of the bright lines relative to the dark lines The bright lines are displaced towards the violet relative to the dark lines by amounts indicating relative velocities of

* *Observatory* xlv 223 1922

† See Gyllenberg, *Arkiv fur Math   Ast   och Fys   K   Svensk Vetenskap*, xiv No 5, 1918

‡ *A N*, ccxix 1 1923 , ccx, 145 1924

§ Merrill, *Ap J* lvi 472, 1922   Perrine *Pop Ast* xxxii 562, 1924

‖ *A J*, xxxiv 190 1923

7 km /sec for stars of 200 days period, and 18 km /sec for stars of 375 days period   Merrill found * that the displacements were not constant throughout the cycle, but were most marked for a month or two after maximum light   It should be remembered that in the case of o *Ceti*, where the spectrum has been photographed throughout the cycle the anomalous behaviour of the bright and dark lines was partly explained by the discovery of a faint companion of early spectral type   This observation was made by Aitken at the suggestion of Joy,† who hoped in this way to clear up some puzzling spectroscopic observations

There is slight but definite evidence that the brightness at maximum is greater for the longer-period variables ‡ and that the stars of longest period affect the plane of the Milky Way §   Another characteristic that changes with the period is the light-curve

The steepness of the rise from minimum to maximum is most marked with the longest periods   The light-curves of the long-period variables cannot be represented accurately by a simple sine-curve, but over long intervals of time a good representation can be given by the use of two or three harmonic terms || Phillips ¶ has divided the variables into two groups according as certain relations exist between the phases of the harmonic terms   If the magnitude is represented by the expression

$$M + P \cos (\theta - 180°) + P' \cos (2\theta - \phi_2) + P'' \cos (3\theta - \phi_3),$$

then the variables group themselves into (*a*) Group I, for which ϕ_3 is always nearly 200°, while ϕ_2 may have any value within a wide range , and (*b*) Group II,

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* Merrill, *Ap J* , lviii 236, 248, 1923
† *Pop Ast* , xxxi 237, 645, 1923   *Pub A S P* xxxv 323, 1923
‡ Ludendorff *A N* , ccxx 150, 1924
§ Turner, *M N R A S* , lxxix 373 1919
|| See Turner, *Mem R A S* , lv 97, 1904
¶ *Journal B A A* , xxvii 5, 1916

for which there is a linear relation between ϕ_2 and ϕ_3, namely, $\phi_3 = 1\ 67\phi_2 - 126\ 8°$ Hagen * pointed out that Phillips's Group I corresponded to stars whose variation was nearly uniform, the time from minimum to maximum being only just less than half a period, and there being no long pause at the maximum or at the minimum   Phillips's Group II Hagen sub-divided into those with a rapid increase of magnitude, whose light-curve resembles the sun spot curve, and those with broad minima   There seem to be certain physical differences corresponding to Phillips's groups, the stars of shorter period (< 200 days) and shorter range of variation belonging to Group I

For Class N stars, Ludendorff † finds that the range of variation in magnitude is less than for the stars of Class M, of which *o Ceti* is the type   This would seem to indicate higher temperatures for Class N stars   In respect, also, of steepness of rise to maximum, Class N stars differ from *o Ceti* in the same sense as stars of Classes K, Mo, M3   But, in one respect, they differ in the other direction   the average period is greater than for the ordinary long-period variables, being nearly 400 days instead of about 300 days   The Class N stars, like the Class Me stars, are all giants

Data of the above nature provide the material by which the views of the theorist as to the early stages of stellar evolution must be checked   The present position seems to be that stars, when they first become visible as condensing masses of cool gas, appear as Me (or N stars), varying in brightness in a period between one and two years   At this stage of their history the sequence of stellar spectra, M8e to Mo, probably represents the line of evolution , the star's temperature rises, its oscillations in brightness become less extreme and shorten in period, the brightness of the star at maximum slowly diminishes, and the star approaches a

* *Ap J* liii 179 1921   † *A N* ccxvii 161 1922

stage of radiative equilibrium. Gradually, changes in the spectra due to growing condensation and rising temperature are followed by the much slower changes due to diminishing mass, but by the time that mass has become the determining factor, the star has probably ceased to figure in the catalogues of variable stars

76. Short Period Variables.—A few stars with periods ranging from 90 days down to 35 days have been grouped by Ludendorff as possibly representing a transition stage from the long-period variables to the Cepheids (called after the type star δ *Cephei*) There is a gap between 45 days, and 67 days with only one star to fill it which comes approximately at the change from Class M to Class K Whether this gap indicates that there is no proper transition from one class of variable to the other, or that the transition stage is passed through comparatively quickly, cannot yet be decided A similar gap occurs among the short period stars for periods between 3 days and 1 day, this gap divides them into two groups, to which the names cluster variable (for the periods less than 1 day),* and Cepheid variable (for periods from 3 to 40 days) have been allotted by certain writers This second gap does not correspond to any other established physical difference between the Cepheid and cluster variables, although it does correspond to a difference in distribution The Cepheids or variables with periods from 3 days to 40 days are confined to low galactic latitudes,† while the variables with periods of less than one day are found in all galactic latitudes In the questions of distribution and the connection of the period with the shape of the light-curve there remain unsolved problems as with the long-period variables, but, on the whole,

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* The shortest known periods are 3 h 14 m 5 8 s for a cluster variable in Messier 3 discovered by Larink (*A N*, ccxiv 71, 1921), and 5 h 41 6 m for a faint eclipsing variable of β *Lyræ* type found by Jordan at 12 h. 28 m. 4 s, and + 27° 16·1' (*A J*, xxxv 44, 1929).

† And to spiral nebulæ, *Pop Ast*, xxxiii. 252, 1925.

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it seems reasonable to link the Cepheid variables on to the long-period variables   This can be more readily accepted, since the old explanation of a Cepheid as a special case of a binary star has proved very difficult to fit in with the following observed facts   On the assumption that a Cepheid is a binary, it is possible to determine the elements of its orbit and the probable sizes of the component stars   Only too frequently the radius of the orbit comes out at a smaller figure than the sum of the radii of the component stars   Again, the spectrum of a Cepheid variable changes continuously in two respects during its light period , the displacements of the lines change continuously, the highest velocities of approach coinciding with maximum brightness, which is not in accordance with the normal condition for a variable binary , also light-maximum corresponds to a star generally a whole Harvard class earlier in type than the star at light-minimum , at no time is there evidence of a secondary spectrum alongside the primary , changes in the colour-index and in the relative strength of various lines indicate higher temperature and greater ionization at maximum , the mean absolute magnitude of the star and also the mean colour-index are simply related to the period of the variation   Everything points to an explanation in terms of one body instead of two   A theory has been worked out by Shapley * and Eddington,† according to which the behaviour of a Cepheid variable is interpreted in terms of a single pulsating star   There are some outstanding difficulties in the narrowness of the absorption lines and in the long-continued maintenance of the pulsation, but the theory at present holds the field   It has even been used by Eddington ‡ to deduce, from the observed slight decrease, about o 1 sec per annum, in the period (5 366 d)

* *Ap J* xl 448, 1914
† *Observatory* xl 290 1917   *M N R A S* , lxxix 2, 177, 1918
‡ *British Association Report*, 1920 45

of δ *Cephei*, a criterion as to the true time-scale for stellar evolution We are not here, however, in the region of assured knowledge, as witness the fact that for η *Aquilæ* the present evidence points to an increasing period,* which is inconsistent with the pulsation theory It is possible that some short-period variables may be wrongly classed with the Cepheids and may be eclipsing variables, in whose case the simple phenomena of an eclipse are modified by tidal disturbances The main bulk of the short-period variables, however, must be classed as single stars

Certain laws governing them have been discovered, and have provided an important clue to the scale of the stellar universe Thus Miss Leavitt discovered † that for the Cepheid variables in the Magellanic clouds there was a connection between luminosity and period—the brighter variables having the longer periods Shapley has extended these results ‡ showing that the relation between the mean absolute magnitude and the period of a short-period variable is very close, the absolute magnitude, and, therefore, the distance of a Cepheid variable being determined from its period with only a small probable error   The chief application has been made to the variables with periods less than one day which occur commonly in globular clusters and give parallaxes for these clusters The greatest distance found for any cluster by this method was for N G C 7006, a distance of 220,000 light-years or 70,000 parsecs   As we have seen already (§ 64) Hubble used the same method to determine the distance of the Andromeda nebula, finding consistent results from 12 Cepheid variables and a value of 950,000 light-years

The luminosity of a Cepheid variable is always very high , the absolute photographic magnitude comes out always brighter than — 0 2,§ the redder variables being brighter

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* Wylie, *Ap J* lvi 231, 1922 Hellerich, *A N* ccxxii 25 1924
† *Harvard Annals* lx 107, 1908   *H C O Circular*, 173 1912
‡ *Ap J* , xlviii 104, 1918   § *Ibid* , xlix 96, 1918

than the bluer ones   The physical implications underlying this limiting magnitude remain to be worked out as part of the general problem of stellar variation

Shapley's conclusions are based on the assumption that the luminosity curve for a cluster variable is the same as that for other short-period variables   Henroteau,* on the other hand, has suggested that cluster variables are of smaller mass than the short-period variables in the galaxy , also that in accordance with the general dependence of temperature and spectrum on mass, the cluster variables are less luminous than the others and less distant than Shapley finds them to be   If Henroteau's separation of the short-period variables into groups of different mass is to be accepted, it may indicate that a dependence of stability on stellar mass is the deciding factor in causing the gaps in the observed periods of variables, to which reference has been made above

One very important application has been made of the study of cluster variables   Examining the light curves in blue and yellow light for a number of variables in the cluster Messier 5, Shapley † found that the delay in the photographic median magnitude on the photovisual median magnitude came out at 0 00012 d $\pm$ 0 0007 d or well within the probable error of the determination   This meant that blue light travelled for 40,000 years without lagging more than a minute or two behind the accompanying yellow light or that the velocities agreed to one part in twenty thousand million   The lack of evidence for dispersion of light in so long a journey has a bearing on the question of the presence of absorbing matter in space and on the size of the particles of which such matter must be composed   The implication is that if any such matter lie between us and Messier 5, it is

* *Pub Dominion Obs Ottawa*, viii 80, 1923
† *Proc N A S ,* ix 386, 1923

composed of particles whose linear dimensions are not of the order of a wave-length of light

77 Theories of Stellar Variation —We have seen how diverse are the different types of variables It is natural that many explanations should have been brought forward to account for them The simple eclipsing of a bright star by a faint companion accounts naturally and successfully for the Algol variables, but fails to account for the short-period or Cepheid variables For this, pulsation accompanied by changes in temperature, luminosity, colour-index and spectrum is suggested as the principal factor in the observed changes For the long-period variable the veil theory, which attributes the variation to periodic changes in the transparency of the outer atmosphere of the star only, seems the most suitable The condensation of clouds of small particles at regular intervals * can be reconciled with the occasional discontinuities detected by Turner † which would be due to the action of some disturbing force either inside or outside the star One class of irregular variable may brighten sporadically through the breakdown of an outer crust and an outrush of hot gases from the interior, while other classes of irregular variables may be explained as caused by the passage of stars through or behind nebulosity an occasional irregular brightening may be due to collision of star and nebula, an occasional fading to occultation of the star by nebulosity When the relative motion of star and nebulosity is sufficiently great, a collision may result in the outburst which we associate with a nova

* P W Merrill, *Pub of the Observatory of the University of Michigan,* ii 70, 1916

† *M N R A S* , lxxvi 480, 1916

STARS WITH PECULIAR SPECTRA

78 Fixed Calcium Lines —In this chapter it is proposed to deal with some of the principal types of stellar spectra which stand outside the normal sequence   In most cases no solution has been proposed for the problem offered by the abnormality in the spectrum, but we start with a case where several solutions have been proposed   A certain number of early Class B stars, whose lines show variable velocity, have present in their absorption spectrum two fixed lines [H] and [K] due to enhanced calcium   Occasionally, as in the case of δ *Orionis*, the sodium [D] lines are also present fixed in position * The velocities shown by these fixed lines are always small when the motion of the solar system has been taken into account   In the special case of novæ, where these lines are also seen, the velocity given by these lines is the solar component reversed, within the error of measurement   The same holds good of J S Plaskett's very massive binary, B D 6° 1309, the most massive star but one so far known † In the case of other binaries the velocity given by the stationary [H] and [K] lines is frequently coincident with the small velocity of the centre of inertia of the binary system , less frequently it shows a different velocity and occasionally it shows a velocity varying with the period

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* *Lick Obs Bull* No 326, 1919 No 337, 1921

† *M N R A S* lxxxii 456, 1922   The probable masses of the components are 86 and 72 times the mass of the sun   υ *Sagittarii* is at least twice as massive (see § 39)

of the binary, but with less range than that given by the other lines   J S Plaskett has recently shown * that in the case of Class O stars the [H] and [K] lines, also the [D] lines, give velocities distinct from those of the corresponding stars, and within the error of measurement agreeing with the reversed solar velocity

Two main theories have been proposed for these lines The one postulates dark interstellar clouds, mostly fixed in space and containing a sufficient proportion of atoms of ionized calcium and of sodium in the right condition to show the absorption lines on the continuous spectrum of the stars The difficulty about this explanation lies in the fact that the types of star in which these lines occur are strictly limited , this is not wholly to be explained by the further fact that these types are the ones best able, from the nature of their spectra, to show the narrow fixed calcium lines The alternative explanation which found favour with R K Young,† is that these lines bear witness to the presence of an outer envelope to the binary star system, which does not share in the oscillations of the binary contained within   There is a difficulty here in that the radial velocity given by the [H] and [K] lines is not always the same as that of the centre of inertia of the binary   The further difficulty of explaining the presence of this outer envelope has to be faced   It is not impossible that in these stars, representing largely the most massive stars, radiation has become so important, relatively to gravitation, that an outer envelope of light gases has been driven out from the central body   Evidence for such outflow of gases followed by the presence of stationary calcium lines is to be found in the history of novæ

A third solution proposed by H H Plaskett,‡ is an ingenious combination of the two previous theories   According

to this view, the intervening cloud postulated in the first hypothesis is near enough to the high temperature star to have enough calcium atoms ionized by the radiation from the star to enable the cloud to show the sharp [H] and [K] lines superposed on the stellar spectra   Some of the Class O stars which show sharp [H] and [K] lines are involved in luminous nebulæ   The extension suggested by Plaskett is that others are involved in or are close behind widespread calcium clouds which are, for the most part, much less dense than the dark clouds recognized by their obscuration of the stellar background   The anomalous cases where the [H] and [K] lines seem to share partly in the oscillations of the lines of Class B binaries may be accounted for by a blend of lines due partly to a stationary cloud of calcium and partly to a moving stellar calcium atmosphere

79 Former Novæ —Two of the novæ of history are now surviving as fairly bright variable stars with peculiar spectra They do not seem to have followed what we may call the usual course, ending as faint Class O stars surrounded by nebulosity, but they seem to have found unusually stable conditions at some earlier stage of their evolution   P Cygni, previously unrecorded, was discovered by Janson on 18th August, 1600   It was observed by Kepler two years later as of the third magnitude, and it ceased to be visible to the naked eye in 1621   It became of the third magnitude again in 1655, but by 1677 it had dropped to magnitude 5 0, and it has maintained nearly constant brightness since   In the slowness of its fading and in the relatively bright condition of stability it differs so markedly from the typical nova that one would be inclined to place it with the irregular variables rather than with the novæ if it were not for its present spectrum, which at once recalls a nova by its type   There are bright lines of hydrogen, helium, oxygen, and nitrogen with dark companions on the violet side *   In the width

* *Ap J* , xxxv 286, 1912

of the bright bands, and in the displacement of the companions the evidence all points to less violent forces at work than with the other novæ   It is tempting to suggest that the more moderate conditions obtaining are connected with the stability in this case of what is generally a very transitory stage with novæ   In terms of the collision theory of novæ, the suggestion would be an unusually small relative velocity of star and nebula

Another nova which maintains an unusual and interesting spectrum is T *Coronæ Borealis* (a star of the second magnitude in 1866), the first nova to have its spectrum investigated   Huggins [*] noted the bright hydrogen lines superposed on a continuous spectrum with many absorption lines. Over fifty years later this star's spectrum was observed [†] and found to be of Class Mo, with bright hydrogen, helium, and nebular lines . the spectrum naturally recalls that of R *Aquarii*

80. Nova Types.—It may here be mentioned that every recognized stage of the quickly varying spectrum of a nova seems to be paralleled in some star, apparently in a much more stable or steady condition   We have given some instances already   R *Monocerotis*, the nucleus of Hubble's variable nebula (see § 72 above), has, like the nebula, a bright line spectrum of hydrogen and ionized metals with dark lines on the more refrangible side of the hydrogen lines. One other variable, notably R *Coronæ Australis*, which is also linked to a variable nebula, shows the same type of spectrum

Perrine [‡] has pointed out that the well-known Wolf-Rayet star, γ *Velorum*, shows still another resemblance to novæ   He has found that absorptions seen at the violet end of broad strong helium bands are sometimes double

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[*] *Proc R S*, xv 146, 1866
[†] *Pub A S P*, xxxiii 263, 271, 1921
[‡] *Ap J*, lii 39, 1920

and vary rapidly in displacement as in the early stages of
novæ, in eight days he gets an increase in radial velocity
indicated by the helium absorptions from — 597 km/sec
to — 1169 km/sec   The phenomena require further study
for their elucidation, but outgoing streams or shells of gas
seem indicated

Another star which bears some close relation with P
Cygni and with novæ generally is DM + 11° 4673, a star
of magnitude 7 7 studied at Michigan by Merrill *   Here,
again, we have bright hydrogen lines with dark companions
on the violet side and bright lines due to ionized metals,
mainly iron, with dark lines due to helium and ionized
silicon   The simultaneous presence of an absorption early
B Class spectrum and of an emission A Class spectrum is
paralleled in N Geminorum 1912   In the case of DM + 11°
4673 we have no evidence of past history as a nova   What
we have is a stage, which is of short duration in a nova,
existing under apparently stable conditions

J S Plaskett has recently reported another remarkable
star with a variable spectrum,† DM + 5° 1267   At times
the spectrum is closely like that of P *Cygni*, bright hydrogen
lines with dark companions displaced to the violet and in
addition a displaced absorption spectrum of diffuse and
rather weak helium lines   Some of the hydrogen absorption
lines are doubled by bright centres   In addition, dark [H]
and [K] are present and strong, and *Mg* II 4481 is present
but weak   Then the metallic lines strengthen relatively to the
helium lines, while at the same time the displacement of the
hydrogen absorption lines to the violet is markedly increased
Next emission begins to appear for the lines due to ionized
iron, titanium and chromium which form the familiar
spectrum of α *Cygni* and of the early stages of novæ   These
metallic emission lines are later accompanied on the violet

* *Pub of Observatory of Michigan*, ii 71 1916
† *Pub A S P*, xxxv 145, 1923

side by absorption lines which strengthen rapidly, the bright metallic lines weakening until the spectrum becomes very like that of α *Cygni*, with the addition of the complex bright hydrogen lines with their displaced dark companions   The displacements of all the absorption lines except the hydrogen lines are small   Taking into account the curious resemblances between the changes in the spectrum of this star and those occurring in the early stages of a nova, we may hope from a study of this star to get further insight into the puzzling problem of the novæ

81 γ **Cassiopeiæ** —Secchi, in 1866, found bright lines in the spectrum of γ *Cassiopeiæ*   This star shows the bright lines of hydrogen and ionized metals, principally iron, along with dark lines of nitrogen, oxygen, and helium   It does not resemble novæ in having dark companions on the violet side of the bright lines, but it is reminiscent of a later stage of a nova's spectrum   Thus, the bright bands are some 5 tenth-metres broad, the breadth being proportional to the wave-length, and bearing the same proportion for different elements   Again, Curtiss * has shown that the bright bands are bordered by several narrow components on each side symmetrically placed on both sides of the centre of the bands and more than doubling their widths   Again, approximately equal intervals separate successive outer maxima of a band   The analogy of a nova would suggest that we look to some extensive atmosphere of the star, coupled with some regularity of circulation in this stellar atmosphere to account for the structure of the maxima in the bands   If such an explanation were acceptable, we might escape the need of explaining the absorptions which reverse centrally and flank strongly the central bright maximum , but the presence of a strong continuous spectrum in this star makes it evident that these absorption bands are real and have to be accounted for in any theory proposed   The existence of

* *Pub of Observatory of Michigan* 11 21, 1916

and vary rapidly in displacement as in the early stages of novæ, in eight days he gets an increase in radial velocity indicated by the helium absorptions from − 597 km /sec to − 1169 km /sec   The phenomena require further study for their elucidation, but outgoing streams or shells of gas seem indicated

Another star which bears some close relation with P *Cygni* and with novæ generally is DM + 11° 4673, a star of magnitude 7 7 studied at Michigan by Merrill *   Here, again, we have bright hydrogen lines with dark companions on the violet side and bright lines due to ionized metals, mainly iron, with dark lines due to helium and ionized silicon   The simultaneous presence of an absorption early B Class spectrum and of an emission A Class spectrum is paralleled in N Geminorum 1912   In the case of DM + 11° 4673 we have no evidence of past history as a nova   What we have is a stage, which is of short duration in a nova, existing under apparently stable conditions

J S Plaskett has recently reported another remarkable star with a variable spectrum,† DM + 5° 1267   At times the spectrum is closely like that of P *Cygni*, bright hydrogen lines with dark companions displaced to the violet and in addition a displaced absorption spectrum of diffuse and rather weak helium lines   Some of the hydrogen absorption lines are doubled by bright centres   In addition, dark [H] and [K] are present and strong, and *Mg* II 4481 is present but weak   Then the metallic lines strengthen relatively to the helium lines, while at the same time the displacement of the hydrogen absorption lines to the violet is markedly increased Next emission begins to appear for the lines due to ionized iron, titanium and chromium which form the familiar spectrum of *a Cygni* and of the early stages of novæ   These metallic emission lines are later accompanied on the violet

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side by absorption lines which strengthen rapidly, the bright metallic lines weakening until the spectrum becomes very like that of α *Cygni*, with the addition of the complex bright hydrogen lines with their displaced dark companions   The displacements of all the absorption lines except the hydrogen lines are small   Taking into account the curious resemblances between the changes in the spectrum of this star and those occurring in the early stages of a nova, we may hope from a study of this star to get further insight into the puzzling problem of the novæ

81 γ **Cassiopeiæ** —Secchi, in 1866, found bright lines in the spectrum of γ *Cassiopeiæ*   This star shows the bright lines of hydrogen and ionized metals, principally iron, along with dark lines of nitrogen, oxygen, and helium   It does not resemble novæ in having dark companions on the violet side of the bright lines, but it is reminiscent of a later stage of a nova's spectrum   Thus, the bright bands are some 5 tenth-metres broad, the breadth being proportional to the wave-length, and bearing the same proportion for different elements   Again, Curtiss * has shown that the bright bands are bordered by several narrow components on each side symmetrically placed on both sides of the centre of the bands and more than doubling their widths   Again, approximately equal intervals separate successive outer maxima of a band   The analogy of a nova would suggest that we look to some extensive atmosphere of the star, coupled with some regularity of circulation in this stellar atmosphere to account for the structure of the maxima in the bands   If such an explanation were acceptable, we might escape the need of explaining the absorptions which reverse centrally and flank strongly the central bright maximum , but the presence of a strong continuous spectrum in this star makes it evident that these absorption bands are real and have to be accounted for in any theory proposed   The existence of

* *Pub of Observatory of Michigan ii 21, 1916*

an extensive outer atmosphere seems a likely and suitable hypothesis to adopt It is supported by the temperature 6800° K (very low for a Bo star), indicated by the continuous spectrum Milne has explained this as due to the molecular scattering of the radiation of shorter wave-lengths by an extensive outer atmosphere Spectroscopic or photographic evidence must be sought for to confirm the actual existence of this envelope

The star μ *Centauri* * closely resembles γ *Cassiopeiæ* in the simultaneous presence of a dark line B type spectrum and a bright line spectrum of hydrogen and ionized metals, ionized iron being the most prominent element represented The star η *Carinæ* (or η *Argus*) also shows these bright metallic lines, accompanied by many bright lines of unknown origin This star has many unknown lines in common with Hubble's variable nebula (see § 72 above), but the elements concerned and the physical condition involved have not yet been discovered

82 β Lyræ —A more complex problem has to be unravelled in the case of the variable β *Lyræ* In this star we have the following factors present First and simplest there is an absorption spectrum of type B8 which is displaced periodically in the same period as that of the complete magnitude variation 12 9 days This spectrum changes in displacement normally as though it were the spectrum of one component of a spectroscopic binary of small eccentricity with a range in radial velocity of 369 km /sec The curve of the light period has two minima as in the case of a normal eclipsing binary, and this B8 spectrum drops slightly in intensity at the principal minimum, suggesting that the component to which it belongs is the brighter of the two stars of the binary system Rossiter † has detected in the velocity‐curve a secondary oscillation, visible near principle minimum, due to the rotation of the partially

* *Proc R S*, lxxiv, 548 1905   † *Ap J*, lx 15 1924

eclipsed component   The other absorption spectrum,
which diminishes rather more markedly in intensity at the
secondary minimum of brightness, is of Class B5   The star
to which it is presumably to be ascribed, shows only very
small, if any, fluctuations in radial velocity, and is presum-
ably far the more massive component of the two   In addi-
tion to these absorption spectra—and undisplaced [H] and
[K] lines of calcium, as so often found in early B type
binaries *—there is present a spectrum of bright bands of
varying intensity and structure which agrees in selection of
lines fairly well with the B5 component   Where the bright
bands occur we often find other dark lines present which may
be structural in the bright bands, or at least refer to the same
source as the bright bands and, perhaps, the B5 absorption
lines   In some cases we may have, corresponding to one
spectral line, a B8 component with its appropriate displace-
ment, a B5 component with its appropriate displacement,
a broad, bright band (several Angstrom units broad), and
several narrow absorption lines crossing or bordering the
bright band   In some cases these extra absorption lines
show a regularity of structure which seems to relate them
closely to the bright band   Similar phenomena have been
noted for novæ and for such a star as γ *Cassiopeiæ* †   In
the case of β *Lyræ* this regularity of structure is almost
more pronounced   Curtiss gives as the displacements of
the dark components of Hγ from the normal positions of
the line $- 7\,30, - 5\,89, - 4\,56, - 3\,17, + 2\,20, + 3\,32,$
$+ 4\,48, + 6\,73$ A   Save for the sixth and eighth com-
ponents the spacing is very regular, the missing centre
components being possibly blended with the B5 or B8
absorption

Many theories have been proposed to account for the
complex phenomena of β *Lyræ*   Most of them postulate a
binary system in an early stage of evolution with the two

* See § 78 above   † See § 81 above

components close together and involved in an extensive atmosphere   According to this view the bright bands are due to the gaseous envelope in part, but also in part to one of the two stars, the variations in the intensity curve of the bright bands being due partly to eclipses of this star and partly to the varying absorptions which its light undergoes in different phases   The width of the bands is due mainly to the rotation of the gaseous envelope, as in the case of novæ   The regular structure in the bands may be traced to the same cause as in novæ (i e   some regularities in the rotational movements of the envelope) or else to some system of regular and successive reversals of lines due to abrupt changes in the density gradient , it cannot, however, yet be claimed that we have found the key to the problem

83 Elements Abnormally Strong —A few stars may be mentioned where the lines of a single element come out more strongly than in general with stars of closely allied spectral condition   Thus we have a *Canum Venaticorum*, a star of spectral class Aop, in which europium is present in a group of lines varying periodically in intensity * and displacement in a manner which suggested to Belopolsky a rotating outer layer or ring of gas   Again, in a *Andromedæ*, Class Aop, we have the lines of ionized manganese present in unusual strength †   In ε *Ursæ Majoris*,‡ Class Aop, we have ionized chromium similarly very strong, while in a *Cygni* § and γ *Cygni* ‖ we have ionized iron and titanium respectively strongly present   φ *Cassiopeiæ*, Class F5,¶ is

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* *Bull de l'Académie Impériale de Sciences de St Petersbourg,* VI Series vii 689 1913   Baxandall *M N R A S* lxxiv 32 1913

† *M N R A S* , lxxiv 250 1914

‡   Researches of the Chemical Origin of Various Lines in Solar and Stellar Spectra Solar Physics Observatory ' 1910

§ Catalogue of 470 of the Brighter Stars, Solar Physics Observatory, 1902

‖ J N Lockyer and Baxandall *Phil Trans* , cci A, 205 1902

¶ W J S Lockyer and D L Edwards, *M N R A S* , lxxxi 479, 1921

transitional between these two so far as iron and titanium and other elements are concerned, but shows ionized strontium slightly stronger than both the others do   Possibly considerations based on Saha's theory will, in time, enable an investigator to place these and other similar stars in an ordered sequence on the giant side of the evolution ladder, but at present they seem to be just outside the main spectral sequence

SPECULATIONS IN COSMOGONY

84 Stellar Evolution —The stellar spectra form a simple linear sequence, and it has generally been thought that the course of evolution for individual stars is either along this sequence in the same direction for all stars, from high to low temperatures, or else along the sequence from low to high temperatures, returning along the same sequence to low temperatures In both theories the ₋tar has been presumed to be condensing steadily from an initial tenuous mass of very low density Eddington has cut right across these views by showing that if a star is in radiative equilibrium its luminosity and its mass are closely related to one another, and that the sequence of spectra represents a sequence of equilibrium points for the evolution of stars of different mass but by no means necessarily a sequence of stages through which individual stars will pass The probable course of evolution of a star is along the line of decreasing mass and decreasing luminosity On the whole we should expect that, if the sequence does represent the course of evolution, we should find that luminosity diminished as we pass along the sequence in the direction in which change is taking place There is some evidence that at both ends of the spectral sequence O-B-A and M-K-G the luminosity diminishes, as we pass along the sequence from the extreme type, and this suggests that both the O and the M stars may represent early stages in stellar evolution So far as the Class O stars are concerned, their masses average

fifty times the mass of the sun, while the average mass of a Class B star is only ten times the mass of the sun * This also indicates, on the whole, an evolution from O to B rather than from B to O

We may look to see what the two classes of stars O and M have in common, beside their great mass and luminosity, which may support this view They both have many members with bright lines in their spectra, and both have high spatial velocities, especially high for the bright line stars In both cases the bright lines are ascribed to tenuous outer atmospheres, and for both classes there is a certain amount of direct evidence for the existence of these outer atmospheres The initial high velocities might be due to the high velocity of (or in) a parent nebula from which the star has come The subsequent slowing down might be due to the obstruction met with by the condensing star and its extensive envelope in its passage through the universe That the slowing down is found as we pass along the spectral sequence may be seen if we take, for instance, the radial velocities of the stars showing fixed calcium lines (and, therefore, probably connected with an extensive envelope) , we find †️ on taking out the solar motion that the average residual velocity of 20 stars of types O5 to O7 is 33 8 km /sec , while the average residual velocity of 29 stars of types O8 to B2 is only 21 3 km /sec The change in velocity is so marked for only a comparatively slight change of spectrum that Campbell's corresponding figure for the B stars, 6 5 km /sec ‡, does not seem to represent an unnatural break in the sequence of velocities, and we may regard the sequence O, B, A as a true physical sequence for early type giants and one which represents a possible line of evolution

Accepting Eddington's view that most stars are in radiative equilibrium, and that evolution may be shown by a

* J S Plaskett, *Pub D A O* , ii 287, 1924
† *Ibid* 336, 1924   ‡ ' Stellar Motions, p 209, 1913

sequence of stars of diminishing mass we come back to a blend of the two historic theories of stellar evolution   For the early type stars we look to the sequence O-B-A, presumably following with F, G, K, etc , and we derive our stars from condensing nebulosity, possibly passing through the planetary nebular stage, P   The dissipation of the nebular envelope follows the condensation of the nucleus, under the intense radiation pressure set up as the nucleus grows in mass, luminosity, and temperature   The subsequent diminution of the mass of the star, which accompanies its decrease in luminosity and temperature, may be due, in part, to the internal destruction of mass and in part to the expulsion of matter from the surface under radiation pressure   It may be conjectured that stars of this early type are formed from the condensation of diffuse nebulosity

For the late type giants, we look to the sequence M-K-G-F or N-R-G-F as representing possibly the early stages, while the star is reaching a condition of radiative equilibrium, the subsequent development being back along the sequence of diminishing mass luminosity and temperature to the dwarf M stage   It is possible that the red giant stars come from the nuclei which form in the arms of spiral nebulæ   They are, in general, less massive than the O, B stars, but they are of the right order of mass for condensations in an outflowing arm of a rotating spiral nebula *   The nuclei would vary in mass, and many of the smaller stars might reach the stage of radiative equilibrium without ever passing through a giant stage at all   All stars alike, once they have reached this stage of equilibrium, would probably evolve along the sequence determined by diminishing mass

To sum up the views advanced above, the evidence points to two sets of massive stars in an early stage of

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* Jeans, ' Problems in Cosmogony," p 219, 1919

evolution   Two separate sources are indicated, namely, diffuse nebulosity and spiral nebulæ   It is suggested that planetary nebulæ, O and B type giants come from diffuse nebulosity, while M and N giants come from condensations in the arms of spiral nebulæ

85   The Solar System —Laplace's Nebular Hypothesis must be our starting-point for any discussion of the cosmogony of the solar system   Starting from a rotating mass of hot gas, Laplace assumed the mass to shrink inwards under the influence of gravitation   Constancy of angular momentum involved an increase in rotational velocity, with consequent instability in the external equatorial regions The outer ring of matter broke off from the main body and subsequently agglomerated round some nucleus in it to form a planet   A succession of such epochs of instability led to the formation of successive annuli and, later, planets Laplace's famous hypothesis has been subjected to many attacks, most of which have been shown, on further investigation, not to rule out the possibility of its truth   It seems certain, however, that the scheme of development must be very much modified in detail, if it is to stand   For instance, considerations of angular momentum and of density show that the ejected matter would have to liquefy shortly after ejection, the planets being born in a liquid or even solid state *   This is not impossible, but there is another difficulty which is inherent in the theory   Carrying out the process of equatorial disintegration with its implications as to density and rotational velocity, we ought to reach a stage where the central body should break up by fission into a double star   There is no evidence of this, and it does not seem possible that our solar system can be the result of a break-up of a primitive gaseous mass owing to mere rotational instability

Some external body is required, to break off from our

* Jeans   Problems in Cosmogony,' Ch XII

central sun detached bodies of the size of the planets   Close passages of individual stars are too rare now to make this hypothesis satisfactory, unless we follow Jeans in his theory of closer packing of the stars in an earlier epoch, an idea developed on quite other grounds   Then we may assume the order of events to have been somewhat thus   As the tide-generating star came near the sun instability was set up, resulting in the tidal ejection of matter from the sun's equator, the matter streaming out in one or two jets   The jets would lie approximately in the plane of passage of the disturbing star, and if two jets were formed they would be diametrically opposite to each other   The rate of ejection of matter would be slow at first, increase to a maximum as the star passed close to the sun, and then decrease again   The filament would lose heat rapidly, especially at the ends, would liquefy there most rapidly and would condense into smaller planets at the two ends and into larger masses near the middle   Thus it comes about on this hypothesis that Jupiter and Saturn are so much larger than the inner or outer planets   The planets would describe orbits round the sun, probably at first of fairly large eccentricities, and the satellites of some of the planets might be formed from them as they passed near the sun by the very same kind of tidal force as that which had torn the planets themselves out of the primary central mass   One result of the resisting medium surrounding the sun through which they passed at first would be to diminish the eccentricities of their orbits to the present low values   There are naturally many problems not resolved by this provisional solution of Jeans, but there is much that is attractive in its combination of tidal and rotational effects

It is not without interest to note the fate of the earlier attempts at cosmogony in the light of Jeans's most recent work   Rotational instability suggested by Laplace and Roche as operative in forming the solar system is found to

apply in modified form, in the building up of stellar systems from gaseous nebulæ through the development of spiral forms   Fission and tidal reactions developed by Darwin for the earth-moon system are found to explain the genesis of binary and multiple star systems   The genesis of the solar system and the earth-moon system remain unexplained   But, whereas Darwin clearly thought that tidal forces cannot have been very important in moulding the solar system, Jeans gives them a very important and, in fact, decisive rôle , only he adds the hypothesis of an external disturbing star passing near in an epoch when stars were more closely packed than at present   One fact emerges clearly   The time for final conclusions in cosmogony has not yet come   The fresh knowledge that crowds in on us on the observational side, especially from the great telescopes of the Pacific coast, may lead to a new set of solutions of the problems of cosmogony within the next century which will differ from those offered by present-day writers as widely as their solutions differ from those of Laplace

APPENDIX I

Letter	Wave length (Rowland) Unless Otherwise Stated	Chemical Origin	Authority for Letter
[Y]	8987 449 I A (head of [Y] band)	Atmosphere	Ab
[x₄]	8806 730 I A	Mg	Ab
[x₃]	8662 101 I A	$Fe-Ca$	Ab
[x₂]	8542 077 I A	Ca	Ab
[x₁]	8498 023 I A	Ca	Ab
[Z]	8226 957 I A	Atmosphere	Ab
[A]	7593 709 I A (head of [A] band)	Atmosphere	Fr
[a]	7164 725 (head of [a] group)	Atmosphere	B P
[B]	6867 457 (head of [B] group)	Atmosphere	Fr
[C]	6563 045	$H\alpha$	Fr
[D₁]	5896 357	} Na	Fr
[D₂]	5890 186		
[D₃]	5875 618 I A	He	———
[E]	5269 723	Fe	Fr
[b₁]	5183 791	Mg	
[b₂]	5172 856	Mg	
[b₃]	5169 220 } 069	Fe	B P
[b₄]	5167 497	Mg	
[F]	4861 527	$H\beta$	Fr
[d]	4383 720	Fe	B P
[G]	{ 4308 081 { 4307 907	Fe } Ca	Fr
[g]	4226 904	Ca	B P
[h]	4102 000	$H\delta$	B P
[1]	4045 975	Fe	B P
[H]	3968 625	Ca	Fr

TABLE—*Continued*

Letter	Wave length (Rowland) Unless Otherwise Stated	Chemical Origin	Authority for Letter
[K]	3933 825	*Ca*	Ma
[L]	3820 586	*Fe—C*	Be
[M]	3727 778	*Fe*	Be
[N]	3581 349	*Fe*	Be
[O]	3440 762⎫ 1 135⎭	*Fe*⎫ *Fe*⎭	Be
[P]	3361 327	*Ti*	Be
[Q]	3286 898	*Fe*	Es
[R]	3179 453	*Ca, Cr*	Es
[r]	3143 879	*Ti*	Ma
[S]	3100 001 (head of group)	*Fe*	Ma
[s]	3046 778	*Ti*	Co
[T]	3021 170	*Fe*	Ma
[t]	2994 527	*Fe*	Co
[U]	2947 99	*Fe*	Co

Authorities —Fraunhofer (Fr), *Denkschrift der K Akad de Wiss zu Manchen,* v 193 1814   Baden Powell (B P), *British Association Report,* 1839   Becquerel (Be) *Bibliothèque Universelle de Genève,* xl 351 1842   Esselbach (Es) *Annalen der Physik,* xcviii 513 1856 , Mascart (Ma) *Annales Scientifiques de l Ecole Normale Polytechnique* 1 237 1864 , Abney (Ab) *Phil Trans ,* clxxvii 653 1880   Cornu (Co), *Spectre Normal du Soleil,* 1881

It should be noted that different writers have adopted the same letters for different lines and some of the above identifications are open to doubt   Thus at the infra red end Langley (*Annals of Astrophysical Observatory of Smithsonian Institution,* 1 1900) has used the symbols [X] [Y] for lines different from those of J W Draper (*Phil Mag* xxii 362, 1843) or of Abney while Higgs (*R S Proc ,* liv 200 1893) described an [a] band of oxygen at λ6276 7, which is different from Draper s [a] though it may be the same as that of Brewster (*Phil Trans* cl 149, 1860)   At the other end of the spectrum, Esselbach has a different set of identifications for the lines [L] [M] [N] [O] [P] [Q] and [R] from those which have been generally adopted   Again Baden Powell s lines [c] [d] [e] have not been identified definitely, though λ4383 720, *Fe* has been allotted

the letter [d]   Baden Powell's original [f] is now the line universally known as [g]   The lines [H] and [K] were formerly known as [H₁] and [H₂] respectively or as [H] and [k]   Rowland's identification of Fraunhofer s [G] line with an iron and calcium pair must be supplemented by an identification with elements of a hydrocarbon band (Newall Baxandall, and Butler, *M N R A S*, lxxvi 640 1916)

APPENDIX II

Reduction of Prismatic Spectrograms

Let n_1 n_2 n_3 be the measured scale-readings for three lines of known wave-lengths λ_1 λ_2 λ_3 It is required to determine the constants λ_0, c n_0 of the reduction formula $\lambda = \lambda_0 + \dfrac{c}{n - n_0}$

The following tabular presentation of the calculation involved I owe to Professor Newall The successive sets of figures of the actual work are represented by numbers enclosed in brackets We take $\lambda_1 < \lambda_2 < \lambda_3$

$(1) = \lambda_1$ $\qquad\qquad\qquad$ $(6) = n_1$

$\qquad (4) = \lambda_2 - \lambda_1$ $\qquad\qquad\qquad\qquad (9) = n_2 - n_1$

$(2) = \lambda_2$ $\qquad\qquad\qquad$ $(7) = n_2$

$\qquad (5) = \lambda_3 - \lambda_2$ $\qquad\qquad\qquad\qquad (10) = n_3 - n_2$

$(3) = \lambda_3$ $\qquad\qquad\qquad$ $(8) = n_3$

$(11) = \dfrac{(4)}{(9)}$ $\qquad (13) = \dfrac{(11)}{(12)}$ $\qquad (15) = (6) \times (13)$

$(12) = \dfrac{(5)}{(10)}$ $\qquad (14) = 1 - (13)$ $\quad (16) = (8) - (15)$ $\quad (17) = \dfrac{(16)}{(14)} = n_0$

$(20) = (17) - (8)$ $\quad (21) = \lambda_1$ $\qquad\qquad\qquad\qquad (18) = (17) - (6)$

$\qquad\qquad (22) = (11) \times (19)$ $\qquad\qquad (19) = (17) - (7)$

$\qquad\qquad (23) = (21) - (22) = \lambda_0$ $\qquad (24) = (22) \times (18) = c$

$\qquad\qquad (25) = \dfrac{(24)}{(20)}$

$\qquad\qquad (26) = (25) + (23) = \lambda_3$

The agreement of (26) with λ_3 provides the check on the computation

An actual reduction of a spectrogram is added by way of illustration

$\lambda_1 = (1) = 4202\ 033$ $n_1 = (6) = 35\ 2551$

(4) 92 097   (9) 15 8343

$\lambda_2 = (2) = 4294\ 130$ $n_2 = (7) = 51\ 0894$

(5) 89 420   (10) 13 3023

$\lambda_3 = (3) = 4383\ 550$ $n_3 = (8) = 64\ 3917$

(11) 5 816297 (13) 0 865244   (15) 30 5043

(12) 6 722130 (14) 0 134756   (16) 33 8874 $n_0 = (17) = 251\ 4722$

(18) 216 2171

(20) 187 0805   (21) 4202 033   (19) 200 3828

(22) <u>1165 486</u> $c = (24) = 251998\ 0$

$\lambda_0 = (23) = 3036\ 547$

(25) <u>1347 003</u>

(26) $\overline{4383\ 550} = \lambda_3$

APPENDIX III

TABLE (a)

TABLE OF CORRECTIONS TO REDUCE WAVE-LENGTHS FROM ROWLAND S SYSTEM TO THE INTERNATIONAL SYSTEM

Wave Lengths	Correction	Wave Lengths	Correction
2950-3125	— 0 12	5375-5400	— 0 20
3125-3250	— 0 13	5400-5500	— 0 21
3250-3450	— 0 14	5500-6050	— 0 22
3450-4150	— 0 15	6050 6500	— 0 21
4150-4350	— 0 16	6500-6570	— 0 22
4350-4550	— 0 17	6570-6750	— 0 23
4550-5125	— 0 18	6750-6850	— 0 24
5125-5300	— 0 17	6850-7000	— 0 25
5300-5325	— 0 18	7000-7200	— 0 26
5325-5375	— 0 19	7200-7400	— 0 27

TABLE (b)

TABLE OF CORRECTIONS TO BE APPLIED TO WAVE-LENGTHS IN AIR AT 15° C AND 760 MM TO REDUCE TO VALUES *in vacuo*

(Meggers and Peters, *Ap J* , 1 61, 1919)

λ	Add	λ	Add	λ_0	Add
2000	0 6512	2250	0 6993	2500	0 7535
2050	0 6601	2300	0 7097	2550	0 7649
2100	0 6695	2350	0 7204	2600	0 7764
2150	0 6791	2400	0 7313	2650	0 7880
2200	0 6891	2450	0 7423	2700	0 7997

TABLE (b)—*Continued*

λ	Add	λ	Add	λ	Add
2750	0 8115	4500	1 2581	6250	1 7251
2800	0 8235	4550	1 2713	6300	1 7386
2850	0 8355	4600	1 2845	6350	1 7520
2900	0 8476	4650	1 2978	6400	1 7655
2950	0 8598	4700	1 3110	6450	1 7789
3000	0 8721	4750	1 3242	6500	1 7924
3050	0 8844	4800	1 3375	6550	1 8058
3100	0 8968	4850	1 3508	6600	1 8193
3150	0 9092	4900	1 3640	6650	1 8328
3200	0 9217	4950	1 3773	6700	1 8462
3250	0 9343	5000	1 3906	6750	1 8597
3300	0 9469	5050	1 4039	6800	1 8732
3350	0 9595	5100	1 4173	6850	1 8866
3400	0 9722	5150	1 4306	6900	1 9001
3450	0 9849	5200	1 4439	6950	1 9136
3500	0 9977	5250	1 4572	7000	1 9271
3550	1 0104	5300	1 4706	7050	1 9406
3600	1 0233	5350	1 4839	7100	1 9541
3650	1 0361	5400	1 4973	7150	1 9676
3700	1 0490	5450	1 5106	7200	1 9811
3750	1 0619	5500	1 5240	7250	1 9945
3800	1 0749	5550	1 5374	7300	2 0080
3850	1 0878	5600	1 5508	7350	2 0215
3900	1 1008	5650	1 5642	7400	2 0350
3950	1 1138	5700	1 5775	7450	2 0485
4000	1 1268	5750	1 5909	7500	2 0620
4050	1 1399	5800	1 6043	7550	2 0756
4100	1 1530	5850	1 6177	7600	2 0891
4150	1 1661	5900	1 6311	7650	2 1026
4200	1 1792	5950	1 6446	7700	2 1161
4250	1 1923	6000	1 6580	7750	2 1296
4300	1 2054	6050	1 6714	7800	2 1431
4350	1 2186	6100	1 6848	7850	2 1566
4400	1 2317	6150	1 6983	7900	2 1702
4450	1 2449	6200	1 7118	7950	2 1837

TABLE (b)—*Continued*

λ	Add	λ	Add	λ	Add
8000	2 1972	8500	2 3325	9250	2 5357
8050	2 2107	8550	2 3460	9300	2 5492
8100	2 2243	8600	2 3596	9350	2 5628
8150	2 2378	8650	2 3731	9400	2 5763
8200	2 2513	8700	2 3867	9450	2 5899
8250	2 2648	8750	2 4002	9500	2 6035
8300	2 2784	8800	2 4137	9550	2 6170
8350	2 2919	8850	2 4273	9600	2 6306
8400	2 3054	8900	2 4408	9650	2 6441
8450	2 3190	8950	2 4544	9700	2 6577
		9000	2 4679	9750	2 6713
		9050	2 4815	9800	2 6848
		9100	2 4950	9850	2 6984
		9150	2 5086	9900	2 7119
		9200	2 5221	9950	2 7255
				10000	2 7391

APPENDIX IV

SECONDARY STANDARDS INTERNATIONAL SYSTEM, IN THE ARC
SPECTRUM OF IRON

3370 789	4118 552	4878 225	5586 772
3399 337	4134 685	4903 325	5615 661
3445 154	4147 676	4919 007*	5658 836
3485 345	4191 443*	4966 104*	5709 396
3513 821	4233 615*	5001 881*	5763 013
3556 881*	4282 408	5012 073	6027 059
3606 682	4315 089	5049 827	6065 492
3640 392	4352 741	5083 344	6137 701
3676 313	4375 934	5110 415	6191 568
3677 629	4427 314	5167 492	6230 734
3724 380	4466 556	5192 363*	6265 145
3753 615	4494 572	5232 957*	6318 028
3805 346	4531 155	5266 569*	6335 341
3843 261	4547 853	5302 315*	6393 612
3850 820	4592 658	5324 196*	6430 859
3865 527	4602 947	5371 495	6494 993
3906 482	4647 439	5405 780	6546 250
3907 937	4691 417	5434 527	6592 928
3935 818	4707 288*	5455 614	6678 004
3977 746	4736 786*	5497 522	6750 163
4021 872	4789 657	5506 784	
4076 642*	4859 758	5569 633	

SECONDARY STANDARDS INTERNATIONAL SYSTEM, IN THE ARC
SPECTRUM OF NICKEL

5857 759   5892 882

SECONDARY STANDARDS, INTERNATIONAL SYSTEM, NEON LINES

5852 488	6074 338	6266 495	6532 882
5881 896	6096 163	6304 789	6598 953
5944 834	6143 062	6334 428	6678 276
5975 534	6163 594	6382 991	6717 042
6029 998	6217 280	6506 528	7032 412

* Found to be unsatisfactory standards, to be replaced by lines marked in the list of tertiary standards, Appendix V, when measured to the necessary degree of accuracy

Suggested Lines for Adoption as Secondary Standards
when Fully Observed

(a) Stable Iron Lines

2375 193	2632 248	2912 161	3155 293
2380 763	2641 654	2926 584	3161 370
2389 979	2656 154	2941 343	3171 353
2399 244	2669 498	2959 996	3184 903
2406 663	2679 066	2976 130	3191 666
2413 313	2699 498	2987 293	3202 562
2443 871	2714 419	2990 394	3217 389
2453 478	2728 026	3011 484	3233 061
2468 885	2746 486	3024 035	3246 015
2474 818	2759 816	3030 150	3265 057
2496 539	2778 847	3040 430	3268 246
2507 904	2797 777	3045 082	3280 268
2512 366	2813 288	3055 268	3292 029
2524 291	2817 506	3068 180	3298 137
2535 610	2828 808	3078 436	3314 746
2543 927	2848 714	3083 745	3317 126
2549 616	2851 798	3091 581	3323 741
2566 921	2858 898	3098 191	3325 468
2584 544	2866 629	3116 632	3337 671
2598 380	2874 176	3125 663	
2612 787	2887 808	3129 334	
2621 677	2899 418	3142 888	

(b) Iodine Lines

5167 478	5364 866	5410 923	5455 623
5171 594	5371 478	5410 955	5497 506
5227 187	5393 157	5415 190	5506 768
5232 908	5393 183	5424 052	5572 860
5266 563	5397 157	5429 726	5586 752
5266 583	5404 150	5434 527	
5324 179	5405 787	5446 936	

APPENDIX V

TERTIARY STANDARDS, INTERNATIONAL SYSTEM IN THE ARC
SPECTRUM OF IRON

3379 023	3581 196	3704 464	3790 096
3380 115	3582 202	3705 568	3794 342
3392 657	3584 664	3707 050	3795 005
3396 981	3585 321	3711 226	3797 518
3401 523	3586 115	3715 915	3798 514
3402 262	3589 108	3719 936	3799 550
3407 463	3594 634	3722 565	3806 702
3413 136	3603 207	3727 622	3867 541
3417 845	3608 862	3732 400	3808 732
3418 511	3617 789	3733 320	3814 527
3424 289	3618 770	3734 868	3815 843
3427 122	3621 464	3737 134	3821 182
3447 282	3623 188	3738 309	3824 445
3450 332	3625 149	3742 623	3825 885
3458 306	3630 352	3745 564	3827 826
3465 864	3631 465	3745 903	3833 313
3476 707	3632 041	3748 265	3834 226
3489 673	3638 300	3749 488	3839 260
3495 291	3645 825	3756 942	3840 440
3497 110	3647 845	3758 236	3841 052
3497 845	3649 509	3760 053	3846 805
3506 501	3651 470	3763 791	3849 970
3521 265	3659 520	3765 544	3852 577
3529 821	3669 524	3767 195	3856 373
3541 088	3679 916	3774 827	3859 914
3542 080	3684 112	3776 457	3867 220
3545 642	3687 459	3781 190	3871 752
3558 519*	3690 731	3785 950	3872 505
3565 382	3695 054	3786 680	3873 764
3576 761*	3702 034	3787 884	3878 022

* Lines selected to replace unsatisfactory secondary standards (see Appendix IV) as soon as measures of the proper accuracy are available

APPENDIX V—*Continued*

3878 575	4009 718	4213 652	4454 386
3883 284	4014 536	4216 188	4459 124
3884 362	4031 966	4219 367*	4461 657
3886 285	4044 616	4226 426	4476 024
3887 052	4045 818	4245 261*	4489 745
3888 518	4062 448	4250 792	4490 088
3895 659	4066 981	4266 970	4514 193
3899 710	4067 277	4267 832	4517 532
3902 949	4067 985	4271 766	4528 622
3903 903	4074 792*	4285 449	4587 136
3910 848	4085 011	4294 130	4602 008
3917 186	4095 977*	4298 043	4619 297
3920 261	4098 185	4305 457	4630 128
3922 915	4100 743	4307 909	4632 918
3925 947	4107 495*	4325 766	4638 019
3927 923	4109 809	4327 101	4654 504
3930 300	4114 451	4337 052	4667 461
3932 631	4120 212	4346 561	4673 171
3937 332	4121 808	4351 552	4678 856
3940 884	4122 523	4358 507	4710 288*
3942 444	4127 614	4367 583	4733 598*
3948 780	4132 062	4369 777	4741 535*
3952 606	4132 905	4383 550	4745 808
3956 461	4137 003	4387 899	4772 818
3956 682	4143 421	4390 956	4786 812
3966 067	4143 873	4404 754	4788 762
3967 424	4154 504	4407 716	4802 886
3969 262	4156 805*	4408 421	4924 776*
3971 327	4170 908	4415 128	4939 691*
3981 776	4175 642*	4422 373	4994 135*
3983 962	4177 599	4430 621	5041 076*
3986 177	4181 761	4435 154	5041 760
3990 380	4184 897*	4442 346	5051 639
3997 397	4202 033	4443 199	5098 706
4005 248	4203 988*	4447 724	5123 725*

* Lines selected to replace unsatisfactory secondary standards (see Appendix IV) as soon as measures of the proper accuracy are available

APPENDIX V—*Continued*

5127 365	5424 038	5984 796	6200 323
5150 845*	5429 701	5987 050	6213 437
5151 916	5445 039	6003 051	6215 150
5166 288	5446 921	6007 961	6219 290
5168 903	5462 959	6008 595	6232 669
5171 601	5463 268	6013 528	6246 350
5198 715*	5473 917	6016 668	6252 567
5202 340*	5476 295	6020 178	6254 267
5216 280*	5476 587	6021 830	6280 623
5227 193	5501 470	6024 051	6297 803
5242 496*	5535 419	6042 083	6301 531
5250 652*	5543 173	6055 983	6302 520
5269 540	5543 944	6078 470	6315 310
5270 360*	5554 872	6089 571	6322 696
5307 365*	5563 613	6102 179	6336 851
5328 537*	5565 688	6103 183	6344 161
5332 903	5572 859	6127 915	6355 040
5341 028*	5576 109	6136 624	6380 753
5378 588	5598 279	6136 998	6400 026
5383 353	5602 958	6147 844	6408 044
5393 188	5624 559	6151 636	6411 678
5397 134	5638 275	6157 734	6421 362
5400 507	5975 354	6165 368	6462 738
5410 890	5976 816	6173 344	6475 639
5415 175	5983 712	6180 225	6518 382
			6575 029
			6609 125
			6663 455

* Lines selected to replace unsatisfactory secondary standards (see Appendix IV) as soon as measures of the proper accuracy are available

APPENDIX VI

Wave Lengths of Lines of Balmer's Series

(Extracted from ' Report on Series in Line Spectra ' A Fowler
Physical Society of London, 1922)

	Wave lengths I A Units (Air at 15° C and 760 mm)		Wave lengths I A Units (Air at 15° C and 760 mm)
Hα	6562 793	Hπ	3697 154
Hβ	4861 327	Hρ	91 557
Hγ	4340 466	Hσ	86 834
Hδ	4101 738	Hτ	82 810
Hϵ	3970 075	Hυ	79 355
Hζ	3889 052	Hϕ	76 365
Hη	3835 387	Hψ	73 731
Hθ	3797 900	Hχ	71 478
Hι	70 633	Hω	69 466
Hκ	50 154	26	67 684
Hλ	34 371	27	66 097
Hμ	21 941	28	64 679
Hν	11 973	29	63 405
H$_0$	03 855	30	62 258
		∞	45 981

APPENDIX VII

WOLFER'S TABLE OF SUN-SPOT MAXIMA AND MINIMA*

Minima	Maxima	Minima	Maxima
1610 8	1615 5	1766 5	1769 7
1619 0	1625 0	1775 5	1778 4
1634 0	1639 5	1784 7	1788 1
1645 0	1649 0	1798 3	1805 2
1655 0	1660 0	1810 6	1816 4
1666 0	1675 0	1823 3	1829 9
1679 5	1685 0	1833 9	1837 2
1689 5	1693 0	1843 5	1848 1
1698 0	1705 5	1856 0	1860 1
1712 0	1718 2	1867 2	1870 6
1723 5	1727 5	1878 9	1883 9
1734 0	1738 7	1889 6	1894 1
1745 0	1750 3	1901 7	1906 4
1755 2	1761 5	1913 4	1917 6

* *V J S der Naturforschenden Gesellschaft in Zurich*, xlvii, 240, 1902

IMPORTANT LINES OF UNKNOWN ORIGIN IN VARIOUS CELESTIAL SPECTRA

The particular spectrum to which any line belongs is denoted by X
The letters in brackets denote the references to the records drawn on

Wave length (I A)	(a) Fraunhofer Spectrum	(b) Chromosphere	(c) Corona	(d) Nebulæ	(e) (f) Wolf Rayet Stars — Dark Lines	(f) Wolf Rayet Stars — Bright Lines	(g) (h) Novæ (Later Stages)	(i) η Carinæ	(j) (k) Me Stars (Bright Lines)	(l) to (r) Various Individual Stars	(s) Aurora
3208 1	—	—	—	—	—	—	—	—	—	—	X
3313	—	—	—	X	—	—	—	—	—	—	—
3328	—	—	X	—	—	—	—	—	—	—	—
3342	—	—	—	X	—	—	—	—	—	—	—
3346	—	—	—	X	—	—	—	—	—	—	—
3388	—	—	X	—	—	—	—	—	—	—	—
3426 2	—	—	—	X	—	—	—	—	—	—	—
3432 5	—	—	—	—	—	—	—	—	—	—	X
3445	—	—	—	X	—	—	—	—	—	—	—
3455	—	—	X	—	—	—	—	—	—	—	—
3601 1	—	—	X	—	—	—	—	—	—	—	—
3611	—	—	—	—	—	X	—	—	—	—	—
3626	—	—	X	—	—	—	—	—	—	—	—
3641 2	—	—	X	—	—	—	—	—	—	—	—
3643	—	—	X	—	—	—	—	—	—	—	—
3648	—	—	X	—	—	—	—	—	—	—	—
3726 16	—	—	—	X	—	—	—	—	—	—	—
3728 91	—	—	—	X	—	—	—	—	—	—	—
3759	—	—	—	X	—	—	—	—	—	—	—
3800 8	—	—	X	—	—	—	—	—	—	—	—

APPENDIX VIII—*Continued*

Wave length (I A)	Fraunhofer Spectrum (a)	Chromosphere (b)	Corona (c)	Nebulæ (d)	Wolf Rayet Stars — Dark Lines (e)(f)	Wolf Rayet Stars — Bright Lines (f)	Novæ (Later Stages) (g)(h)	η Carinæ (i)	Me Stars (Bright Lines) (j)(k)	Various Individual Stars (l to r)	Aurora (s)
3840 2	—	—	—	X	—	—	—	—	—	—	—
3860	—	—	—	—	—	—	—	—	—	(p) (m)	—
3868 74	—	—	—	X	—	—	—	—	—	—	—
3883	—	—	—	—	(f)	—	—	—	—	—	—
3907 26	—	—	—	—	—	—	—	—	(j)	—	—
3911 2	—	—	—	—	—	—	—	—	—	(n)	—
3932 54	—	—	—	—	—	—	—	—	(j)	—	—
3938 19	—	—	—	—	—	—	—	—	(j)	—	—
3938 40	X	X	—	—	—	—	—	—	—	(m)	—
3945 0	—	—	—	—	—	—	—	—	—	(m)	—
3952 1	—	X	—	—	—	—	—	—	—	—	—
3954 1	—	—	—	—	—	—	—	—	—	(p)	—
3965 3	—	—	—	—	(e)	—	—	—	—	—	—
3967 51	—	—	—	X	—	—	—	—	—	—	—
3967 58	—	—	—	—	—	—	—	—	(j)	(l) (o)	—
3983 8	—	—	—	—	—	—	—	—	—	—	—
3986 7	—	—	X	—	—	—	—	—	(j)	—	—
4006 82	—	X	—	—	—	—	—	—	—	—	—
4021 4	—	X	—	—	—	—	—	—	—	—	—
4022	—	—	—	—	(f)	—	—	—	—	(m)	—
4024 4	—	—	—	—	—	—	—	—	—	—	—
4025 13	—	—	—	—	(e)	—	—	—	—	(l)	—
4038	—	—	—	—	—	—	—	—	—	—	—
4050 7	—	—	—	—	(f)	—	—	—	—	—	—
4056 5	—	—	—	—	—	X	—	—	—	—	—
4063 6	—	—	—	—	(f)	—	—	—	—	—	—
4067 92	—	—	—	—	(e)	—	—	—	—	—	—
4068 62	—	—	—	X	—	—	—	—	—	—	—
4069 5	—	—	—	—	—	—	—	—	—	(q)	—
4070	—	—	—	—	—	X	—	—	—	(l) (p)	—
4075 9	—	—	—	—	—	—	—	—	—	—	—

APPENDIX VIII—*Continued*

Wave length (I A)	Fraunhofer Spectrum (a)	Chromosphere (b)	Corona (c)	Nebulæ (d)	Wolf Rayet Stars — Dark Lines (e)(f)	Wolf Rayet Stars — Bright Lines (f)	Novæ (Later Stages) (g)(h)	η Carinæ (i)	Me Stars (Bright Lines) (j)(k)	Various Individual Stars (l) to (r)	Aurora (s)
4076 22	—	—	—	X	—	—	—	—	—	—	—
4084 5	—	—	—	—	(f)	—	—	—	—	—	—
4085 2	—	—	—	—	(e)	—	—	—	—	—	—
4085 8	—	—	X	—	—	—	—	—	—	—	—
4086 5	—	X	—	—	—	—	—	—	—	—	—
4091 6	—	—	—	—	(e)	—	—	—	—	—	—
4099 22	—	—	—	—	(e)	—	—	—	—	—	—
4122 7	—	X	—	—	—	—	—	—	—	(n) (m)	—
4128 7	—	—	—	—	—	—	—	—	—	(n)	—
4132 3	—	—	—	—	—	—	—	—	—	(n)	—
4137 3	—	X	—	—	—	—	—	—	—	—	—
4138 65	—	—	—	—	—	—	—	—	(k)	—	—
4152 84	—	—	—	—	(e)	—	—	—	—	—	—
4155 2	—	—	—	—	—	X	—	—	—	—	—
4156 51	—	—	—	—	(e)	—	—	—	—	—	—
4159 19	X	—	—	—	—	—	—	—	—	—	—
4162 94	—	—	—	—	(e)	—	—	—	—	—	—
4163 6	—	—	—	—	—	X	—	—	—	—	—
4178 82	—	—	—	—	—	—	—	—	(k)	—	—
4182 3	—	—	—	—	—	—	—	—	—	—	X
4184 00	X	—	—	—	—	—	—	—	—	—	—
4186 93	—	—	—	—	(e)	—	—	—	—	—	—
4188 73	X	—	—	—	—	—	—	—	—	—	—
4191 6	—	—	—	—	—	—	—	—	—	—	—
4198 24	X	—	—	—	—	—	—	—	—	(p)	—
4212 33	—	—	—	—	(e)	—	—	—	—	—	—
4215 74	—	—	—	—	—	—	—	—	(k)	—	—
4231 2	—	—	X	—	—	—	—	—	—	—	—
4233 35	—	—	X	—	—	—	—	—	(k)	—	—
4241	—	—	X	—	—	—	—	—	—	—	—
4244 09	—	—	—	—	—	—	—	X	—	—	—

APPENDIX VIII—*Continued*

Wave length (I A)	Fraunhofer Spectrum (a)	Chromosphere (b)	Corona (c)	Nebulæ (d)	Wolf Rayet Stars — Dark lines (e)(f)	Wolf Rayet Stars — Bright Lines (f)	Novæ (Later Stages) (g)(h)	η Carinæ (i)	Me Stars (Bright Lines) (j)(k)	Various Individual Stars (l) to (r)	Aurora (s)
4244 6			X								
4258 4										(m)	
4273 4										(m)	
4275 4										(n)	
4275 86					(e)						
4276 85								X			
4287 29								X			
4301 10	X										
4303 94	X		X								
4311			X								
4320 4					(f)						
4325 6						X					
4358 94								X			
4359 3			X								
4363 20				X							
4372 7									(j) (k)		
4376 8										(p)	
4391 6					(e)						
4413 87								X			
4416 26						X					
4441 2						X					
4446 38		X						X		(l)	
4448									(j)		
4448 13						X					
4456 8								X			
4457 80									(k)		
4458 83		X									
4462 1		X									
4465 6					(f)			X			
4474 70									(k)		
4511 46											

APPENDIX VIII—*Continued*

Wave length (I A)	(a) Fraunhofer Spectrum	(b) Chromosphere	(c) Corona	(d) Nebulae	(e)(f) Wolf Rayet Stars Dark Lines	(f) Wolf Rayet Stars Bright Lines	(g)(h) Novæ (later Stages)	(i) η Carinæ	(j)(k) Me Stars (Bright Lines)	(l) to (r) Various Individual Stars	(s) Aurora
4516 4	—	—│	—	—	—	X	(g)	—	—│	—	—
4518 34	—	X	—	—	—	—	—	—	—│	—	—
4521 54	—	—	—	—	—	—	—	—	(k)	—	—
4533 2	—	—	X	—	—	—	—	—	—	—	—
4537 8	—	—	—	—	(f)	—	—	—	—	—	—
4555	—	—	—	—	—	X	—	—	—	—	—
4567	—	—	X	—	—	—	—	—	—	—	—
4571 5	—	—	—	X	—	—	—	—	—	—	—
4578 84	—	—	—	—	—	—	—	—	(k)	—	—
4586	—	—	X	—	—	—	—	—	—	—	—
4600 6	—	X	—	—	—	—	—	—	—	—	—
4603 8	—	—	—	—	(e)	—	(h)	—	—	—	—
4610	—	—	—	—	—	—	(g)	—	—	—	—
4631 16	—	—	—	—	(e)	—	—	—	—	—	—
4658 2	—	—	—	X	—	—	—	—	—	—	—
4666	—	—	—	—	—	X	—	—	—	—	—
4680 8	—	—	—	—	(f)	—	—	—	—	—	—
4695 5	—	—	—	—	(f)	—	—	—	—	—	—
4699 33	X	—	—	—	—	—	—	—	—	—	—
4700 16	X	—	—	—	—	—	—	—	—	—	—
4701 4	—	—	—	—	—	—	—	—	—	—	—
4711 4	—	—	—	X	—	—	—	—	—	(r)	—
4725 5	—	—	—	X	—	—	—	—	—	—	—
4728 17	—	—	—	—	—	—	—	X	—	—	—
4731 3	—	X	—	—	—	—	—	—	—	(l)	—
4740 2	—	—	—	X	—	—	—	—	—	(m)	—
4757 3	—	X	—	—	—	—	—	—	—	—	—
4761 8	—	X	—	—	—	—	—	—	—	—	—
4779	—	—	X	—	—	—	—	—	—	—	—
4786 2	—	—	—	—	—	X	—	—	—	—	—
4810 8	—	X	—	—	—	—	—	—	—	—	—

APPENDIX VIII—*Continued*

Wave length (I A)	(a) Fraunhofer Spectrum	(b) Chromosphere	(c) Corona	(d) Nebulæ	(e)(f) Wolf Rayet Stars — Dark Lines	(f) Wolf Rayet Stars — Bright Lines	(g)(h) Novæ (Later Stages)	(i) η Carinæ	(j)(k) Me Stars (Bright Lines)	(l) to (r) Various Individual Stars	(s) Aurora
4814 60	—	—	—	—	—	—	—	X	—	(l)	—
4889 46	—	—	—	X	—	—	—	X	—	—	—
4958 91	—	—	—	X	—	—	—	—	—	—	—
5006 84	—	—	X	—	—	—	—	—	—	—	—
5073	—	—	X	—	—	—	—	—	—	—	—
5118	—	—	X	—	—	—	—	—	—	—	—
51307	—	—	—	—	—	X	—	—	—	—	—
5250 9	—	—	—	—	—	X	—	—	—	—	—
5284 11	—	X	—	—	—	—	—	—	—	—	—
5302 9	—	X	X	—	—	—	—	—	—	—	—
5325 57	—	X	—	—	—	—	—	—	—	—	—
5425 25	—	X	—	—	—	—	—	—	—	—	—
5536	—	—	X	—	—	—	—	—	—	—	X
5578 0	—	—	—	X	—	—	—	—	—	—	—
5737	—	—	—	X	—	—	—	—	—	—	—
5755	—	—	—	—	(e)	—	—	—	—	—	—
5919 19	—	—	—	—	(e)	—	—	—	—	—	—
6278 33	—	—	—	X	—	—	—	—	—	—	—
6302	—	—	—	X	—	—	—	—	—	—	—
6313	—	—	—	X	—	—	—	—	—	—	—
6364	—	—	X	—	—	—	—	—	—	—	—
6374 3	—	—	—	X	—	—	—	—	—	—	—
6548 1	—	—	—	—	(e)	—	—	—	—	—	—
6558 25	—	—	—	X	—	—	—	—	—	—	—
6583 6	—	—	—	X	—	—	—	—	—	—	—
6730	—	—	—	X	—	—	—	—	—	—	—
7009	—	—	—	X	—	—	—	—	—	—	—
7138	—	—	—	X	—	—	—	—	—	—	—
7325	—	—	—	X	—	—	—	—	—	—	—

REFERENCES

In the compilation of the preceding list a wide range of publications on varied celestial spectra was reviewed. The references to the actual records from which the lines were taken are given below

(*a*) Rowland s   Preliminary Table of Solar Spectrum Wave-Lengths

(*b*) Chromosphere—

    1 Kensington, *Phil Trans*, cxcvii 208, 1901

    2 Dyson *Phil Trans*, ccvi A, 438 1906

    3 Mitchell, *Ap J* xxxvii 407 1913

(*c*) Corona—

    Campbell and Moore *Lick Obs Pub*, x 10 1918

(*d*) Nebulæ—

    Wright, *Lick Obs Pub* xiii following p 242, 1918, *Pub A S P* xxxii 63 1920

(*e*) and (*f*) Wolf-Rayet Stars—

    Plaskett, H H *Pub D A O*, *Victoria* 1 No 30, 1922

    Wright, *Lick Obs Pub* xiii 222 1918

(*g*) *N Geminorum*, 1912—

    Adams and Pease *Ap J*, xl 296 1914

(*h*) *N Aquilæ*, 1918—

    Lunt, *M N R A S*, lxxx 530, 1919

(*i*) *η Carinæ*—

    Moore and Sanford *Lick Obs Bull*, viii 59, 1913

    Lunt, *M N R A S* lxxix 621 1919

(*j*) *o Ceti*—

    Stebbins, *Lick Obs Bull*, ii 91 1903

    Adams and Joy, *Pub A S P* xxx 193 1918

(*k*) Me Stars—

    Merrill *Ap J* lviii 195 1923

(*l*) *a Canum Venaticorum*—

    Belopolsky, *A N* cxcvi 1 1913

(m) α *Cygni*—

Publication by Solar Physics Committee, " Catalogue of 470 of the Brighter Stars, 30 1902

(n) ε *Ursæ Majoris*—

Publication by Solar Physics Committee " Researches on the Chemical Origin of Various Lines in Solar and Stellar Spectra, 31, 1910

(o) α *Andromedæ*—

Lockyer and Baxandall, *Proc Roy Soc*, lxxvii 550 1906

(p) θ *Aurigæ*—

Lockyer and Baxandall, *Proc Roy Soc*, lxxvii 550 1906

(q) ε *Orionis*—

Publication by Solar Physics Committee, ' Comparison of the Spectra of Rigelian, Crucian and Alnitamian Stars, 6 1914

(r) R *Aquarii*, Merrill (privately)

(s) Aurora—

Vegard *Phil Mag* xlvi 193 1923

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